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E.A. Heinrichs *Editors*

Integrated Pest Management of Tropical Vegetable Crops

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Foreword

The world's population surpassed 7.3 billion in early 2016 with predictions that it will exceed 9.6 billion by 2050. While the global population has increased over 70 %, per capita food consumption has been almost 20 % higher. The United Nations Food and Agriculture Organization (UN-FAO) estimates that 805 million people were chronically or acutely undernourished during the period of 2012–2014. Most undernourished are in Asia, but sub-Saharan Africa is the only region where hunger prevalence is more than 30 %. Unfortunately, the absolute number of malnourished people is increasing. Of the 805 million undernourished, most are in Southern Asia (35 %), sub-Saharan Africa (27 %), and Eastern Asia (19 %). Globally, poor nutrition causes 45 % of deaths of children under 5, which amounts to 3.1 million each year. Sixty-six million primary age children in the developing world attend school hungry, consisting of 23 million in Africa alone.

The world now faces three major challenges: (1) to match the rapidly changing demand for food from a larger and more affluent population; (2) to supply food in ways that are environmentally and socially sustainable; and (3) to ensure that the world's poorest people are no longer hungry. Although staple food is provided by rice and wheat, food from horticultural crops such as vegetables and fruits is significant in solving the global food shortage. Vegetables are an important component of the human diet and are also important in combating rural poverty. Vegetables are rich in, and a comparatively cheaper source of, minerals, salts, and vitamins. An acre's yield of vegetables is very high in vitamins and minerals (four to ten times more than cereals). Vegetables are an important source of farm income providing regular work throughout the year and producing a high quantity of nutritious food per acre. Ongoing consumer demand for vegetables in developed countries has contributed to an increase in the trade volume of fresh produce. This, in turn, has promoted the growth of small farms and the addition of new products, creating more rural and urban jobs and reducing the disparities in income levels among farms of different sizes.

Although vegetables potentially play a major role in global food security, insects, plant pathogens, weeds, nematodes, and vertebrate pests are major constraints to tropical vegetable production. The traditional methods of pest and disease control in vegetables include heavy applications of dangerous chemicals and are cost prohibitive and increasingly ineffective for smallholder farmers. In addition, the indiscriminate use of pesticides has caused widespread environmental damage. As a result of the increasing problems encountered with the use of pesticides, the concept of Integrated Pest Management (IPM) has emerged. IPM is based on ecological principles and is compatible with a sustainable and environmentally benign agricultural system. The IPM approach allows farmers to protect their crops from pests and diseases without investing in toxic pesticides and suffering from the environmental and health costs that inevitably ensue.

This book, *Integrated Pest Management of Tropical Vegetable Crops*, is an excellent reference for researchers, extension personnel, technology transfer specialists, and university students. The book reports on two decades (1993–2014) of success, innovation, and collaboration of the USAID-supported Feed the Future IPM Innovation Lab in promoting the IPM concept in vegetable production. The aim of this IPM project is to reduce crop loss, increase farmer income, reduce pesticide use, improve IPM research and education, improve pest monitoring, and increase the involvement of women in IPM decision making and program design. To achieve this vision, the IPM Innovation Lab approach involved networking, private sector involvement, technology development, and technology transfer. During the 20-year period, the program worked in West Africa, East Africa, Eastern Europe, Central Asia, South Asia, Southeast Asia, and Latin America and the Caribbean. The program's success relies upon the ability of researchers and collaborators to develop IPM techniques such as grafting, mulching, trapping, and the development of resistant varieties through biological control and then bundle these new developments into packages targeted towards specific vegetable crops, regions, seasons, and pest problems.

This book describes the importance of vegetables in combating hunger and malnutrition, the IPM packages developed for various vegetable crops in different regions, case studies of IPM packages for various vegetable crops in Asia and Latin America, the transfer of IPM technology to the smallholder vegetable farmers, and the economic and environmental impact of IPM on vegetable production in the tropics.

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Guru Ghosh

Preface

The year 2050 looms as an important threshold. That year the planet will be populated with 9.6 billion people, and we will have to dramatically increase food production in order to feed them. By 2050, an additional 2.5 billion people will live in urban areas. With larger urban populations comes changing food demand: higher quality and more diversity. It also puts pressure on supply chains which are often weak and undeveloped in developing countries. This increased population density is projected to increase demand for food production by 70 % notably due to changes in dietary habits in developing countries towards high-quality food.

Access to nutritious food is a key dimension of food security. In Africa and Asia, urban households spend up to 50 % of their food budgets on cheap "convenience" foods that are often deficient in the vitamins and minerals essential for health. Fruits and vegetables are the richest natural sources of micronutrients. But in developing countries, daily fruit and vegetable consumption is just 20–50 % of Food and Agriculture Organization (FAO)/World Health Organization (WHO) recommendations. The human body needs major minerals such as iron, calcium, phosphorus, and magnesium as well as trace elements and vitamins essential for good health, especially vitamins such as ascorbic acid, which vegetables provide. Vegetables grown by rural farmers have the potential to improve food security, nutrition, and incomes globally.

However, there are numerous abiotic and biotic constraints to vegetable production. The biotic constraints—insect pests, plant pathogens, nematodes, weeds, and vertebrates—severely reduce the yield and quality of vegetables. Yield losses can reach as high as 100 % in some cases.

As the demand for vegetables has grown worldwide, production has intensified, and there has been a concomitant expansion in the use of synthetic insecticides to control pests and plant pathogens. Concerns over potential health and environmental dangers, increased pest resistance to pesticides, and continued prevalence of pest-induced crop losses have stimulated the search for alternatives to pesticides. This has led to the concept of Integrated Pest Management (IPM), a management system philosophy that emphasizes increased information to make pest management decisions and integrate those decisions into ecologically and economically sound production.

This book reports on the role of the former USAID (United States Agency for International Development)-sponsored IPM Collaborative Research Support Program (CRSP; currently the IPM Innovation Lab (IL)) in promoting the IPM concept in vegetable production in Africa, Asia, and Latin America. The objective is to explain the research and technology transfer procedures followed in developing model IPM programs for tropical vegetable crops. It should serve as a valuable resource for IPM practitioners as well as for national agricultural programs, NGOs, and international agencies involved in promoting food production and global food security. The editors and authors of the chapters in this book have written from a firsthand knowledge and experience gained from global experience in developing IPM programs.

Chapter 1 discusses the need for global food security and the importance of vegetables and other crops in contributing to food security. Vegetables play a major role in combating malnutrition and in increasing rural income. It also stresses the importance of increasing food production through scientific research and the transfer of production technologies to farmers and the importance of government policies in promoting scientific research and technology transfer.

Chapter 2 explains the contrasting differences in the evolution of IPM in developed and developing countries. IPM in developed countries has digressed and now emphasizes control with the application of pesticides and pesticide resistance management. IPM in developing countries emphasizes avoidance via cultural control, physical control, host plant resistance, botanical pesticides, biopesticides, behavioral manipulation, landscape management, conservation of natural enemies, and biological control. The IPM packages of practices consisting of these technologies are detailed.

Chapter 3 summarizes more than two decades of research results to identify virus diseases on tropical vegetable crops and describes progress to enhance the local capacity for in-country diagnosis and implementation of integrated disease management practices. A need to address a wide range of vegetable crops was identified by the IPM Innovation Lab. To meet these needs, a team of virologists was organized to work across countries and regions with IPM specialists to document disease problems in priority crops: mainly tomato, peppers, melons, various gourds and cucurbits, and locally preferred vegetables such as eggplant, okra, yard-long bean, and fruits (passion fruit, tree tomato).

Trichoderma spp. (fungal antagonists), which serve as alternatives to pesticides, are discussed in Chap. 4. Biocontrol agents such as *Trichoderma* spp. are harmless to humans, cheaper than pesticides, and highly effective throughout the crop growth period and have high rhizosphere competence and competitive saprophytic ability. Most developing countries do not have the technical knowledge to mass produce *Trichoderma* spp. Hence knowledge- and skill-oriented workshops have been conducted in Asia and Africa through the IPM Innovation Lab. The antagonistic organisms have proven to be effective against several soilborne pathogens offering multiple disease protection and are now being used by farmers to ensure sustained residue-free food production by delivering antagonists through seed and soil.

Prior to the emergence of the plant protection sciences, farmers evolved many cultural practices through trial-and-error experiences to minimize the damage caused by insect pests. In recent years, pesticides have become the major pest-control method. As a result of the problems caused by pesticides, physical, mechanical, and cultural controls serve as an alternative to pesticides in an IPM approach. Physical, mechanical, and cultural control tactics are described in Chap. 5.

Chapters 6, 7, 8, 9, 10, 11, 12, and 13 consist of case studies describing the research in the development of IPM components, the evaluation of the technologies in field studies, the integration of the components into a package of practices and their evaluation in farmers' fields, transfer of the IPM packages to farmers, and the economic benefits provided to the farmers who adopt the IPM packages. These studies indicate that there are similarities in the development and implementation of IPM packages in different countries in spite of differences in geography, crops, pests, soil types, and climatic conditions. Hence, these case studies serve as model examples which can be followed on other crops grown under different conditions in other countries.

Chapters 6, 7, and 8 describe the packages of practices developed for the integrated management of cruciferous vegetable crops, okra, and onion in India. Chapter 6 explains that cruciferous crops are one of the most important contributors to the total vegetable production and the most commonly consumed vegetables in India. Crucifers are attacked by a wide range of pests and diseases which significantly reduce their quality and yield. This chapter discusses the bioecology of economically important pests and diseases of cruciferous crops and the IPM packages developed to manage them.

Pests and diseases are major constraints to the quality and quantity of okra with total losses of about 35–40 % in India. Chapter 7 describes the biology and etiology of the key pests and diseases of okra and describes the development of components that are integrated into a package of practices as alternatives to the use of pesticides. The IPM approach termed the "okra IPM package" registered significantly lower populations of insect pests and disease incidence with an increase in plant growth and natural enemy populations.

Onion, cultivated on 1,204,000 ha, is the fourth most important commercial vegetable crop in India as well as an important export crop. Pests and diseases play a major role in production, leading to yield losses of 10–15 %. Chapter 8 discusses the major pests and diseases attacking onions and their importance as yield constraints. To cope with these pests and diseases, IPM components have been developed as alternatives to pesticides. These components consist of cultural controls, behavioral approaches, host plant resistance, biological control, and biopesticides. These components have been integrated in the development of IPM packages which are described in detail. The efficacy of the IPM package in managing pest and disease populations and the economic impact of the package, compared to the farmers' practice, are described.

Chapters 9 and 10 describe the development of IPM packages for naranjilla and potatoes in the Ecuador foothills and highlands, respectively. In Ecuador's Andean foothills, many colonists have planted naranjilla (*Solanum quitoense*), a perennial shrub member of the section *Lasiocarpa* whose fruit is used to make a widely consumed juice. Naranjilla is highly profitable for small-scale farmers, representing one of the few economically profitable land uses in these environmentally vulnerable areas. However, naranjilla production in Ecuador is threatened by severe pest problems, and the main solution—continual land clearing—is environmentally unsustainable. The IPM CRSP invested more than 10 years of research to create an IPM package for naranjilla producers, and Chap. 9 describes the process of IPM package development, its components, and some of the potential impacts of aggressive diffusion.

Chapter 10 explains the research and outreach effort employed to develop and diffuse IPM packages for potatoes in highland Ecuador. Potato production in Carchi is essential for livelihoods of small-scale producers, and these producers face growing pest problems. The research project identified key pest constraints, worked with farmers and local scientists to develop and test appropriate IPM technologies, and created packages tailored to farmer needs. The research was especially relevant because farmers in the area were using large quantities of highly toxic chemicals as a part of their pest-control regimes, and human and environmental health were suffering as a result.

Vegetable crops grown in Bangladesh suffer serious losses due to different insects and diseases. Before the introduction of IPM, farmers indiscriminately used different chemical pesticides to control vegetable pests. The IPM IL (CRSP), with active cooperation of Bangladesh Agricultural Research Institute (BARI) scientists, has developed different IPM packages for several vegetable crops. These IPM packages are described in Chap. 11. IPM tactics include use of resistant varieties for eggplant to control wilting diseases; use of grafting, soil amendment, and tricho-compost to combat soilborne diseases; and use of pheromone trapping, infected shoot clipping, and release of biocontrol agents to control several pests for the management of cucurbit fruit fly and eggplant shoot and fruit borer.

Over- and misuse of chemical pesticides in vegetables in Nepal have brought about a renewed interest in Integrated Pest Management (IPM) from both public and research sectors. Through the support of the IPM IL, full season IPM packages for important vegetable crops—tomato, cucumber, and cauliflower—were developed and evaluated as described in Chap. 12. IPM packages, which are holistic suites of IPM recommendations and practices, include seed/seed bed treatment using *Trichoderma*/*Pseudomonas*, soil solarization, roguing virus-infected plants, use of nylon nets in the nursery, insect monitoring using pheromone traps, vegetable grafting against diseases, use of plastic trays and coco-peat, neem-based pesticides, biofertilizers, biocontrol agents, etc. IPM packages significantly reduce chemical pesticide use and are also economically competitive with farmer practices. More than 80 % of the farmers under the IPM IL have been recorded to have adopted vegetable IPM practices and packages.

In Uganda, intensified production of marketed vegetable crops has led to changing agricultural practices, including crop and input intensification; a changing set of pests; and increased use and reliance on synthetic pesticides to manage these pests. Chapter 13 describes a participatory IPM program with smallholder farmers to develop and disseminate alternative pest management strategies for managing priority pests and reducing pesticide usage on tomato. Baseline farmer surveys indicated that farmers were spraying a variety of pesticides 12–24 times per growing season. The component technologies developed into a package and disseminated to farmers included a bacteria wilt-resistant tomato variety MT56, mulching, staking, and a minimum spray schedule of three to four pesticide sprays per season. Impact assessments indicated that yields were 40 % higher when the package was used and reduced production costs (by reducing the number of sprays) that led to higher net revenues for IPM-practicing tomato farmers.

Chapter 14 provides a summary of economic and environmental impact assessments of IPM on tropical vegetables. It focuses primarily, but not exclusively, on studies conducted by the IPM CRSP (Innovation Lab). Methods for measuring IPM impacts are briefly reviewed, followed by results of empirical studies. Finally, lessons are drawn for IPM programs and for IPM impact assessment. The total estimated impacts of IPM on tropical vegetables exceed $500 million for just the small set of careful empirical evaluations that have been completed, making tropical vegetable IPM research and extension a highly profitable public investment.

Blacksburg, VA, USA Rangaswamy Muniappan
July 1, 2016 E.A. Heinrichs

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Chapter 1
IPM for Food and Environmental Security in the Tropics

E.A. Heinrichs and Rangaswamy Muniappan

Abstract The global population, by 2050, is estimated to reach nine billion people. Studies show that during the years 2000–2010, worldwide crop production increased at a rate of 23 % while the number of harvested acres increased at only 9 %. In order for supply to meet the growing demand, farmers need to maximize their yield. In fact, crop yields have fallen in many areas because of declining investments in research and infrastructure, as well as increasing water scarcity, land degradation, climate change and biotic stresses (insect pests, weeds, pathogens and vertebrates).

Innovative crop protection is a vital element in the science behind increasing crop yields. The Integrated Pest Management (IPM) approach has the potential to reduce the probability of catastrophic losses to pests, minimizes the extent of environmental degradation and contributes to food security. The modern concept of pest management is based on ecological principles and includes the integration and synthesis of different components/control tactics into an Integrated Pest Management system. IPM, in turn, is a component of the agroecosystem management technology for sustainable crop production. The IPM control tactics are (1) Biological control: protection, enhancement and release of natural enemies, (2) Cultural practices: crop rotations, sowing time, cover cropping, intercropping, crop residue management, mechanical weed control, (3) Chemical: minimizing the use of synthetic pesticides in favor of biopesticides (fungi, bacteria and viruses) and biochemical pesticides (insect growth regulators, pheromones and hormones—naturally occurring chemicals that modify pest behavior and reproduction and (4) Resistant varieties: varieties bred using conventional, biotechnological and transgenic approaches. The effective transfer of IPM technology and its adoption by farmers are vital in increasing food production. Participatory IPM research, through its involvement of farmers, mar-

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keting agents and the public, is designed to facilitate diffusion of IPM technologies. A number of strategies have been implemented over time in efforts to accelerate diffusion of IPM globally. These strategies and their comparative merits are discussed. Fortunately, the science-based Green Revolution, referred to as the Doubly Green Revolution, is underway, tapping into the ongoing revolution in genetics, molecular biology, plant physiology, modern ecology and information technology. "Appropriate plant protection technology" is playing a vital role in the Doubly Green Revolution and the struggle for food security. In this respect, the quote of the Father of the Green Revolution, Norman Borlaug is appropriate. "The only way that the world can keep up with food production to the levels that are needed with a growing world population is by the *improvement of science and technology*, and with the *right policies that permit the application of that science and technology*."

Keywords Biodiversity • Biocontrol agents • Biopesticides • Climate change • Ecological engineering • Insect pests • Plant diseases • Resistant varieties • Technology transfer • Weeds

Food Security

The World Food Summit of 1966 defined '***Food Security***' as existing "when all people at all times have access to sufficient, safe, nutritious food to maintain a healthy and active life." Commonly, the concept of food security is defined as including both physical and economic access to food. ***Food insecurity*** is part of a continuum that includes hunger (food deprivation), malnutrition (deficiencies, imbalances, or excess of nutrients), and famine. The United Nations declares a "famine" when at least 20 % of households in an area face extreme shortages with a limited ability to cope; acute malnutrition rates exceed 30 % and the death rates exceed two persons/day/10,000 persons (Grace Communications Foundation 2015).

Global food security is difficult to accurately measure. The FAO (2014) estimates that 805 million (M) people were chronically or acutely undernourished during the period of 2012–2014. This is slightly down from 854 M people in 2005 (Sanchez and Swaminathan 2005). This accounts for about 14 % of the world's population. Most undernourished people are in Asia, but sub-Saharan Africa is the only region where hunger prevalence is more than 30 %. Unfortunately, the absolute numbers of malnourished people are increasing. Of the 805 M undernourished people, most are in Southern Asia (35 %), sub-Saharan Africa (27 %) and Eastern Asia (19 %) (Wikipedia. Food Security. https://en.wikipedia.org/wiki/Food_security). About 50 % of the hungry are in smallholder farming households. Twenty percent are in landless rural households (Sanchez and Swaminathan 2005). Globally, poor nutrition causes 45 % of deaths of children under 5 – 3.1 M each year. Sixty-six million primary age children in the developing world attend class hungry, consisting of 23 M in Africa alone.

Challenges to Achieving the Goal of Food for All

Crop production has dramatically increased in the past half-century, allowing for a slight decrease in the proportion of the world's people that are hungry despite a doubling of the world's population (Godfray et al. 2010). Still, more than one in seven persons today still do not have access to sufficient protein and energy from their diet, and even more suffer from micronutrient malnourishment. Global food security will remain a worldwide concern for the next 50 years and beyond (Rosegrant and Cline 2003).

The world now faces three major challenges: (1) to match the rapidly changing demand for food from a larger and more affluent population to its supply; (2) to do so in ways that are environmentally and socially sustainable; and (3) to ensure that the world's poorest people are no longer hungry. This challenge requires changes in the way that food is produced, stored, processed, distributed, and accessed. These challenges are as radical as those that occurred during the eighteenth and nineteenth century industrial and agricultural revolutions and the twentieth century Green Revolution.

Crop yields have fallen in many areas because of declining investments in research and infrastructure, as well as increasing water scarcity, land degradation, climate change and biotic stresses (insect pests, weeds, pathogens and vertebrates) (Rosegrant and Cline 2003; Wikipedia. Food Security. https://en.wikipedia.org/wiki/Food_security).

Agricultural Pests and Diseases

The Green Revolution has led to a significant increase in world food supplies, thus saving hundreds of millions of people in South Asia from succumbing to famine (Bloomberg 2014; Conway 1999). At the same time, the increased use of agrichemicals accompanying the Green Revolution has often favored the population increase of pests, and some minor pests have assumed the status of major pests. In addition, the misuse of pesticides has led to problems of pesticide resistance and pest resurgence (Dhaliwal et al. 2010).

Since the beginning of agriculture in about 8000 BC, farmers have been in competition with harmful organisms: animal pests (insects, mites, nematodes, slugs, rodents, birds), plant pathogens (bacteria, fungi, viruses), and weeds (i.e., competitive plants), collectively called pests affecting crop products grown for human use and consumption (Oerke 2006). Globally, food plants are damaged by an estimated 10,000 insect species, 30,000 weed species, 10,000 diseases (caused by bacteria, fungi, viruses, and other microorganisms) and 1000 species of nematodes (Dhaliwal et al. 2010). However, less than 10 % of the total identified pest species are generally considered major pests that need to be controlled.

Globally, an average of 35 % of crop yield is lost to pre-harvest pests and 10–20 % to post-harvest pests (Oerke et al. 1999). Actual field crop losses due to pests vary considerably depending on the region, year, crop and crop production practice. Oerke (2006) has estimated the global pest-induced monetary losses by a group of crops (soybean, wheat, cotton, maize, rice, potatoes) during the years 2002–2003. The estimated losses were 26–29 % for soybean, wheat and cotton, and 31 %, 37 % and 40 % for maize, rice and potatoes respectively. Overall, weeds produced the highest potential losses (34 %), with animal pests and pathogens being less important (losses of 18 % and 16 % respectively). In addition to the field losses, insects, rodents and microorganisms also cause losses to grains in storage.

Climate Change Effects on Biotic Stressors and Biocontrol Agents

Global climate change refers to a change in the long-term weather patterns that characterize the regions of the world (Selvaraj et al. 2013). These seasonal and long-term changes affect the flora, fauna and population dynamics of insect pests, severity of plant pathogens, composition and abundance of weed species, activity and abundance of natural enemies, species extinction and efficacy of crop protection technologies. Kiritani (2006) has described the effects of global warming on the population dynamics and distribution of arthropods in Japan. The mean surface temperature in Japan rose by 1.0 °C from 1956 to 2006. This extent of global warming will impact a change in (1) pest status, (2) range expansion, (3) winter mortality, (4) number of generations per year, and (5) phenology.

Change in Pest Status

Kiritani's (2006) study indicated a change in pest status of rice pests in Japan. The rice stem borers *Chilo suppressalis* and *Scirpophaga incertulas* (Lepidoptera: Pyralidae) were severe pests from 1945 to 1965, followed by a 30-year period, which marked an increase in the prevalence of plant hoppers and leafhoppers and the severity of the viral diseases they transmit. Since 1995, the damage caused by various species of rice bug has become more severe than ever before.

Range Expansion

Global warming will allow those species directly limited by temperature to expand northward. More than 50 butterfly species showed a northward range expansion, and 10 species of butterflies that were previously migrant, became established in the Nansei Islands.

Winter Mortality

It is hypothesized that the winter survival of insects will be improved by an increase in winter temperature, but the evidence for this is scarce. The winter mortality of the adult green stink bug, *Nezara viridula*, was predicted to be reduced by 15 % by each rise in 1 °C. There are examples of short-term changes in climatic conditions affecting insect pest population (Gregory et al. 2015). Conditions in the UK during the 1975–1976 time frame were particularly beneficial for aphids in terms of early development and reduced overwintering mortality, leading to large increases in cereal aphid populations (Jones 1979).

Number of Generations

Kiritani (2006) predicted that with a 2 °C increase in mean annual temperature, the number of generations/year of rice insects would average a 1.17 increase. The insect predator and parasitoid groups are expected to produce an additional two to four generations each year. However, predacious spiders will not experience a generational increase.

Phenology

An increase in the mean annual temperature may cause overwintering insects to emerge earlier in the spring. In Kiritani's (2006) study, the average temperature in 1997 was 2 °C higher than that of the 1960–1996 period, a record high for the region. That year, several arthropod species, including aphids, thrips, lepidopterans and mites, emerged earlier than in previous years.

Climate Change and Plant Pathogens

Increased CO_2, temperature, rainfall and humidity, due to climate change parameters, are predicted to have an impact on the distribution of pests and diseases in Nepal (Malla 2008). It is predicted that diseases abundant in the plains ecosystem may gradually shift up to the hills and mountains. Already, some pathogens of important crops from the Terai zones that have adapted to the hills and mid-hills (e.g. rust and foliar blight) may affect agricultural production.

Elevated CO_2

Elevated CO_2 has direct effects on plant growth and can also result in indirect effects such as reduced expression of resistance to pathogens (Gregory et al. 2015). Elevated levels of both ozone and CO_2 can also affect the expression of resistance directly. Effects on pathogen growth can also be observed (Chakraborty and Datta 2003). Pathogen fecundity has been shown to increase under elevated CO_2 levels, leading to enhanced rates of pathogen evolution. Overall, the effects of elevated CO_2 concentration on plant disease can be positive or negative, although in a majority of the examples reviewed by Chakraborty (2005) disease severity increased.

In Nepal, climate change effects on fruit and vegetables are becoming issues of concern. An open top chamber was used to study the response of tomatoes to elevated CO_2. Tomato yield in kg. increased by 279 % and fruit number by 205 % under increased CO_2 as compared to field conditions outside the chamber (Malla 2008).

Temperature and Drought

Plant pathogens can be differentially affected by temperature (Gregory et al. 2015). Under drought stress, pathogens can have reduced symptoms and impact. Resistance genes can show a temporary loss of expression due to drought stress. Findings suggest that the efficacy of resistance genes may be compromised under extreme and variable climatic conditions.

Rainfall and Humidity

Throughout the summer of 1846, the Irish had high hopes for a bumper potato harvest. But the cool, moist summer had been ideal for the spread of potato late blight caused by *Phytophthora infestans* (The History Place 2000). By harvest time, the blight had struck ferociously, spreading at 50 miles per week, destroying nearly every potato plant in its path. Thus, the infamous Irish potato famine began. Temperatures and moisture stress are the most important environmental factors affecting potato late blight.

In the USA in 2009, environmental conditions were conducive to *P. infestans* development. Colder than average temperature and greater than average rainfall caused a major *P. infestans* infestation of tomato plants in the eastern states (Wikipedia.http://en.wikipedia.org/wiki/Phytophthora_infestans).

Extreme Weather Events and Pathogens

Extreme events can have indirect or secondary consequences as illustrated by the outbreaks of potato late blight in Canada. The epidemics of 1994–1996 were due to genotypes of *P. infestans* from distant regions, which were associated with the unusual tracks moving up the eastern seaboard of the USA (Peters et al. 1999).

Climate Change and Biological Control Agents

Natural pest control is an important ecosystem service provided by biodiversity (Wilby and Thomas 2002). The dollar amount spent globally on pesticides is a good indicator of how much we value pest control. World pesticide expenditures reach more than $30 billion annually with insecticide accounting for about one-third of the total amount (Kiely et al. 2004). In addition, pesticide usage is expected to triple by 2025 (Tilman et al. 2001). Populations of natural enemies are being decimated by the heavy use of pesticides. The destruction of biological control agents results in resurgence of insects and promotes the shift of non-pest species to pest status. Therefore the conservation of biological control agents is an ecologically sustainable method of pest management.

Approximately 99 % of potential crop pests are controlled by natural enemies (DeBach 1974). These natural biological control agents save farmers billions of dollars annually by protecting crops and reducing the need for pesticides (Naylor and Ehrlich 1997). Therefore, the impact of climate change on the destruction and abundance of natural enemies is a major factor in the integrated management of crop pests.

Climate change can have a direct effect on the natural enemies of pest species and an indirect effect via the herbivore (pest) quality and via the host plants (Thompson et al. 2010).

Climate Change vs. Geographic Range Shifts

The plant species produced in a region are expected to change over time with climate change as growers choose crops that optimize economic returns (Gerard et al. 2011). As climate change is a gradual process, it is predicted that most pests and their natural enemies will move with the host plants.

Modification in the geographical distribution of crop plants, insect hosts and their parasitoids may result from a number of processes, including differences in migratory potential of insects (and their host plants), the appearance of green bridges (new plant species providing favorable overwintering sites), and the destabilization of resident ecosystems (Cannon 1998).

Climate Change vs. Natural Enemy Physiology

Climate change factors act directly, on the physiological processes of insect natural enemies, greatly affecting their functioning and thus, their ability to control insect pests (Jervis and Kidd 1996). Beneficial insects will be influenced by warmer conditions in similar ways to those of insect pests, with accelerated growth rates, smaller body size and reduced longevity (Atkinson 1994). Climate change parameters also affect the degree of damage caused by pests by influencing the generation time ratio (GTR) (the predator's generation time to that of its prey) (Kindlmann and Dixon 1999). A low GTR = potentially effective biocontrol and high GTR = potentially ineffective biocontrol.

Climate Change vs. Interspecific Population Dynamics

Natural enemies with very narrow and specific host ranges, a highly desirable attribute for classical biological control programs, may be more sensitive to climate change than generalist herbivores and predators (Selvaraj et al. 2013). Parasitoids are more likely to be affected by climate change than plant herbivores because they depend on the capacity of the lower trophic levels to adapt to these changes. Those who kill their hosts only when their hosts are fully developed (koinobiont) are particularly vulnerable, as their host must remain alive throughout the parasitoid development.

Climate Change vs. Intraspecific Population Dynamics

Temperature has a direct effect on the pathogenicity of fungi such as *Beauveria bassiana* and *Metarhizium anisopliae*, which can either be virulent, causing extensive and rapid mortality in days, or virtually benign, with the same hosts surviving for weeks or even months. Temperature can affect host susceptibility to parasitoids. Observations demonstrate that high temperatures can enhance survival of parasitized hosts (Thomas and Blanford 2003).

Plant Mediated Effects vs. Natural Enemies

Increases in CO_2, changes in water availability and increases in temperature, alter plant physiology, growth and distribution, all of which have effects on the plant herbivores and those who prey on them (Gerard et al. 2011). Changes in host plant quality in response to elevated CO_2 may cause shifts in herbivore and natural enemy fitness. Elevated CO_2 generally leads to a decrease in the nutritional value of plants. Under elevated CO_2, cotton aphid survival significantly increased as larval development of the predacious ladybird took significantly longer (Gao et al. 2009; Gerard et al. 2011). Therefore, it can be predicted that aphid pests will become more damaging in the future. Increases in herbivore development time, due to changes in plant quality as caused by elevated CO_2 or moisture stress, is implicated in reduced parasitism of the cassava mealybug *Phenacoccus herreni* (Catatalud et al. 2002).

Climate Variability Effects on Natural Enemies

The efficacy of biocontrol agents is highest under a stable environment (Gerard et al. 2011). In addition to the predicted increase in mean temperature, CO_2 and shifts in rainfall distribution, climate variability is also expected to increase. Extreme events, such as droughts, foods and unseasonable frosts are predicted to occur more frequently (Gerard et al. 2013). While many species have mechanisms to cope with extremes, they require time to acclimatize and/or enter the resistant state. In general, low temperature extremes cause a decrease in longevity, fecundity and mobility of biocontrol agents. Extreme temperatures can also affect behavior linked to host location and evaluation. Generally, the host is more resistant to extremes in climate variability than the natural enemy. Thus, extreme weather events such as droughts are followed by pest population explosions because of the loss of natural enemy action.

Climate Change and Weeds

Climate change leads to altered environmental conditions such as temperature and precipitation that directly affect arable weeds (Peters et al. 2014). Climate change also influences weeds indirectly by enforcing adaptations of farming methods, such as crop choice, sowing time, harvesting date, and other agronomical practices (Fleming and Vanclay 2010). Climate change effects are categorized into three distinct types of shifts occurring at different scales: (1) range shifts at the landscape level, (2) niche shifts at the community scale, and (3) trait shifts of individual species at the population scale (Peters et al. 2014).

In order to persist in a local habitat, weed species have to respond to changes in the local environment (Woodward and Cramer 1996). Generally, plant species have three options to avoid extinction (Pautasso et al. 2010): (1) Migration with a favorable climate, which leads to alterations of the distribution of weeds—a process called "*range shift*," (2) Acclimation to changes in climatic conditions refers to the response of species within their phenotypic plasticity (Pearman et al. 2008). The fitness and competitive ability of weeds are either reduced or enlarged (Barrett 2000). Consequently, the realized niche is being altered, which leads to *niche shifts*. (3) Adaptation to changes in climatic conditions, which are driven by natural selection, result in *trait shifts* (Carroll et al. 2007).

Range Shifts

Range shifts represent the transformation of the distribution area of species and occur at landscape scale, i.e. at a geographical area extending from several arable fields up to a few hundred kilometers (Petit et al. 2011). With recent climate change, plant species are expected to track the climate favorable to their growth (Jump and Peñuelas 2005). Rising temperatures can cause species range boundaries to move toward the poles (Walther et al. 2002). Thus, C 4 weeds, such as *Amaranthus retroflexus*, *Setaria* spp., *Digitaria* spp. and *Sorghum halepense* are expected to extend their distribution range to locations further north (Clements and Ditomasso 2011).

It is assumed that increased precipitation levels during winter will shift the range of many weed species moderately eastward in Europe (Bergmann et al. 2010). The effect of climate change on the number of weed species is likely to be more pronounced in northern regions of Europe, as the number of weeds is lower there than in southern regions (Fried et al. 2008).

Niche Shifts

In ecosystems, every species occupies an ecological niche. Changing climatic conditions leads to a transformation of the size and shape of the niche pool. Niche gaps result from disturbances caused by extreme climatic events, such as extreme wind, frost, rain and other mechanical disruptions. Niche gaps directly affect the abundance and type of weeds, due to the removal of plants caused by disturbance (Nogues-Bravo 2009). Niche gaps are “opportunity space” for exotics and invasive species. Due to their large niche size and few, but very stable linkages, “keystone species” exert a large effect on the community. Weed communities with a history of frequent herbicide treatments often lack keystone species, which leads to less stable arable communities that are often prone to the establishment of invasive species (Fox and Fox 1986).

Trait Shifts

The term “trait shift” refers to visible and measurable alterations of morphological or physiological attributes of individual plant species caused by changes in climatic conditions. Trait shifts are often related to phenology, morphology, physiology and reproduction. The adjustment of sowing dates to changing spring and autumn temperature conditions that German farmers practiced in the past decade is relevant in this context (Peters et al. 2014). For example, the temperature range for the germination of *Chenopodium ficifolium*, as measured in the 1950s, was between 30 and 40° (Lauer 1953); whereas it was between 0 and 30° in the late 1980s. This trait shift mainly occurred as an adaptation to earlier spring crop sowing dates, which were adapted by farmers during that period of time in Germany.

Implications of Climatic Change for Agronomic Weed Research

Land use, agricultural practices and abiotic environmental conditions, including climate, select for certain weed species based on the suitability of their eco-physiological profiles. In recent years, weeds that show traits related to long growing seasons have increased in Europe (Peters et al. 2014). In former times, the sum of growing degree days was too low to allow the seeds of *A. theophrasti* to fully ripen during the growing season in Central Europe (Westermann et al. 2012); longer growing seasons during the past 50 years (Menzel et al. 2006) allowed the species to successfully produce ripe seeds. Climate change involving warmer temperatures will allow these species to successfully reproduce and to extend the range further north in Central Europe.

Among the weed species that benefit from climate change, there are those that already possess or will develop opportunistic attributes related to climate change. Attributes, such as drought or heat tolerance, the C_4 photosynthesis type, the date of first flowering, high seed production, small and light seeds, high dispersal ability, a rapid life cycle, and regeneration after disturbance have been identified to be particularly relevant with regard to the predicted future changes (Peters et al. 2014). Wetter and milder conditions will increase the survival of some winter annuals such as *Stellaria media* and *Sisymbrium* species that already possess strong traits related to these climatic conditions (Hanzlik and Gerowitt 2012).

Crop management often selects weeds whose attributes are similar to those of the crop and weeds that are adapted to frequent disturbance such as intensive management (Essl et al. 2011). For example, due to the limited specificity of herbicides, selection processes and cruciferous weeds that are closely related to oilseed rape, such as *Sisymbrium* species, are now common in German fields (Hanzlik and Gerowitt 2012). In maize crops, typical weed species appear to be genetically related to millets, such as *Echinochloa crus-galli*, *Setaria* spp., and *Digitaria* (Mehrtens et al. 2005). They appear to be the result of short-term selection processes, and their presence is mainly caused by modern management practices (Peters et al. 2014).

Agronomic practices should therefore mitigate niche gaps via cultural methods (e.g. crop rotation, sowing time, and tillage) (Peters et al. 2014). Integrated weed management (IWM) combines cultural methods with occasional herbicide use (Anderson 2007). However, repeated herbicide treatments will cause new and additional niche gaps.

Prerequisites for Global Food Security: The Role of Appropriate Plant Protection

In a paper entitled "*How to Feed the World in 2050*" by FAO (2009), the authors predicted that by 2050, the world's population will reach 9.1 billion, 34 % higher than in 2009. Most of this entire population increase will occur in developing countries. Urbanization will continue at an accelerated pace, and about 70 % of the world's population will be urban. Urban income levels will be much higher than they are now. In order to feed this larger, more urban and richer population, food production must increase by 70 %. Annual cereal production will need to rise to about 3 billion tons, from 2.1 billion tons produced in 2009. New and traditional demand for agricultural products will exert increasing pressure on already scarce agricultural resources. While agriculture will be forced to compete for land and water with sprawling urban settlements, it will also be required to serve on other major fronts. Adopting to and contributing to the mitigation of climate change, helping preserve national habitats and maintaining biodiversity, farmers will need new technologies to produce more from less land, with fewer hands.

Given these challenges, sustainable production at elevated levels is urgently needed (Oerke and Dehne 2004). The availability and conservation of fertile soils and the development of high-yielding varieties are major challenges to agricultural production. Safeguarding crop productivity by protecting crops from damage by weeds, arthropods and pathogens is a major requisite for the provision of food and feed in sufficient quantity and quality.

Oerke et al. (1999) estimated in a comprehensive study of pest-induced losses, covering eight major crops, that pre-harvest losses due to pests would account for 41 % of the potential value of output, with 15 % attributed to insects, and 13 % attributed to weeds and another 13 % to plant pathogens. An additional 10 % of the potential losses were attributed to postharvest pests.

Integrated Pest Management Concept

What is the role of Integrated Pest Management in minimizing pest-related crop losses and thus, contributing to food security and minimizing the level of hunger and poverty? According to the USDA (1993) "IPM is a management approach that encourages natural control of pest populations by anticipating pest problems and preventing pests from reaching economically damaging levels. All appropriate techniques are used, such as enhancing natural enemy populations, planting pest resistant/tolerant crops, adapting cultural management practices, and using pesticides judiciously." In developing countries, food supply often suffers from poor crop production technology, and crop losses are high, due to inadequate pest control. Intensification of food production can only be realized by the implementation of IPM into cropping systems. This approach has the potential to reduce the probability of catastrophic losses to pests and minimize the extent of environmental degradation. This approach requires (1) the development of IPM models for key pests of crops grown for domestic consumption, (2) training of farmers and technology transfer agents (government extension services, NGOs and private consultants), and (3) availability of ecologically sound compounds and alternatives to insecticides (e.g. novel pesticides, bio-pesticides and cultural practices, such as grafting, pest resistant/tolerant varieties, biological control agents, etc.).

IPM has four distinct yet interrelated objectives (SP-IPM 2008): (1) Food security, (2) Cost effectiveness, (3) Environmental protection and (4) Safeguarding human health.

1. **Food security**- IPM ensures that harvests are sufficiently bountiful and of sufficient quality to adequately nourish the farm families and others who depend on them. Thus, IPM is a strategy designed to decrease hunger and improve nutrition of the chronically hungry and vulnerable.
2. **IPM is cost-effective production for competitiveness**- IPM is an expanding toolkit of cost-effective renewable options that can help farmers cut production losses without having to pay the high costs of non-renewable inputs. The competitiveness refers to the ability to meet the health and quality standards of the market. IPM options make it easier for farmers to meet the minimum pesticide residue standards and to obtain certification as producers of organically grown food. This is a key ingredient in increasing farm income and alleviating rural poverty.
3. **IPM is directly concerned with protecting the environment**- IPM pays attention to, takes advantage of and sometimes enhances existing ecosystem processes. This includes the natural balance between biological control agents (predators, parasitoids and entomopathogens) and prey, plants' chemical defenses, and the mix and density of local vegetation. In exploiting these factors, IPM attempts to minimize the use of chemical pesticides, although these products remain integral to IPM and frequently play a key role in plant protection. However, of great importance is the maintenance of biodiversity, especially the protection of non-target organisms from the negative effects of broad-spectrum pesticides.
4. **IPM aims to safeguard human health**- IPM contributes to human health by reducing inappropriate pesticide regimes, thereby cutting the risks of farm families to pesticide exposure. In addition, IPM contributes to human health through improved food safety by minimizing mycotoxin and chemical pesticide contamination of food, feed and the environment.

Integrated Pest Management Components

Evolution of the concept and terminology of pest management spans a period of almost a century (Dhaliwal and Arora 1996). Over the years, there has been a shift from a chemical-based pest management paradigm to an ecologically/biologically-based pest management paradigm (Maredia et al. 2003). Forces during the shift, are environmental concerns, sustainability, human health, food safety, biodiversity, pest resistance and global trade. The modern concept of pest management is based on ecological principles and includes the integration and synthesis of different components/control tactics into an Integrated Pest Management system. IPM, in turn, is a component of the agroecosystem management technology for sustainable crop production. The IPM control tactics are:

- **Biological control**: protection, enhancement and release of natural enemies.
- **Cultural practices**: crop rotations, sowing time, cover cropping, intercropping, crop residue management, mechanical weed control, etc.
- **Chemical**: Minimizing the use of synthetic pesticides in favor of biopesticides (fungi, bacteria and viruses) and biochemical pesticides (insect growth regulators, pheromones and hormones—naturally occurring chemicals that modify pest behavior and reproduction).
- **Resistant varieties**: Varieties bred using conventional, biotechnological and transgenic approaches.

Biological Control

The inherent ecological stability and self-regulating characteristics of natural ecosystems are lost when humans simplify natural communities through the shattering of the fragile thread of community interactions. However, this breakdown can be repaired by the enhancement of functional biodiversity in agroecosystems. Biodiversity performs a variety of ecological services. One is the regulation of the abundance of undesirable organisms (pests) through predation, parasitization and competition (Altieri and Nicholls 1998). Predators and parasitoids act as natural control agents, resulting in the regulation of herbivore numbers in a particular ecosystem. This regulation has been termed 'biological control' and has been defined by DeBach (1974) as "the action of parasites, predators or pathogens in maintaining another organism's population density at a lower average than would occur in their absence." As practiced, biological control can be self-sustaining, distinguishing itself from other forms of pest control by acting in a density-independent manner; i.e., natural enemies increase in intensity and destroy a larger percentage of the pest population as the density of that population increases and vice versa (DeBach and Rosen 1991). Applied biological control can be considered a strategy to restore functional biodiversity in agroecosystems by adding, through classical and augmentative biocontrol techniques, 'missing' entomophagous insects or by enhancing naturally occurring predators and parasitoids through conservation and habitat management (Dhaliwal and Heinrichs 1998).

Growing nectar-rich flowering plants on rice bunds to provide food and shelter for parasitoids is a means of promoting conservation of natural enemies through the ecological engineering approach (Heong 2011). In addition to conserving specific natural habitats, ecological engineering methods can be used to augment biodiversity by the planting of nectar-rich flowering plants on the bunds (levees) of irrigated rice fields. These flowers provide nectar for bees and other species that can enhance the pollination of fruit crops in the rice landscapes. In addition, the nectar is also a food resource for many hymenopteran parasitoids, especially those that regulate rice pest species, such as planthoppers, leafhoppers, stem borers and leaf folders. Ecological engineering fields in Vietnam, with bunds enriched with nectar rich flowers, had significantly higher parasitism and predation of planthopper eggs that are deeply embedded in the rice tissues. Farmers in these villages had stopped using insecticides and were harvesting similar or higher yields, but with substantial increases in profits from the reduced insecticide use. In Jin Hua, China, hybrid-rice fields surrounded by sesame and nectar-rich flowering plants, with no insecticides applied, had significantly higher densities of arthropod parasitoids and predators as well as frogs. Again, yields in these fields were the same as in rice fields without ecological engineering that had been sprayed three times. Therefore, ecological engineering contributes to decreased rural poverty and promotes environmental security.

Classical biocontrol (the introduction of alien species from the center of origin of the introduced targeted pest) has contributed significantly to global food security. An outstanding example is the biological control of the cassava mealybug (*Phenacoccus manihoti*), a pest that was introduced into Africa from South America. The exotic neotropical parasitoid *Anagrus lopezi* was later collected in South America and transferred to Africa by IITA in the 1970s. The parasitoid, established in 29 African countries, caused a 90 % drop in losses due to the cassava mealybug (SP IPM 2008) and provided farmers with a net profit of US $90 per hectare in 27 countries of Sub-Saharan Africa (Nuenschwander 2007). This was considered a major achievement in the area of insect science (Nwilene et al. 2008).

A more recent example of the role of classical biological control in contributing to food security is demonstrated by the papaya mealybug story. The papaya mealybug is an outstanding example of classical biological control (Muniappan et al. 2006; Myrick et al. 2014). A native of Mexico, the papaya mealybug invaded India in 2006 when farmers in Tamil Nadu first began reporting that a new pest was attacking papaya (*Carica papaya* L.). Numerous applications of insecticide were made, but papaya losses were severe, and the pest spread to several other crops. The pest was identified in 2008 as the papaya mealybug *Paracoccus marginatus*, (Muniappan et al. 2008) and a classical biological control program was initiated. Three parasitoids, *Acerophagus papayae*, *Pseudoleptomastix mexicana*, and *Anagrus loecki* (Hymenoptera: Encyrtidae) were imported from Puerto Rico in July 2010. *Acerophagus papayae* was released and multiplied. Excellent control of the papaya mealybug was obtained within 5 months, pesticide usage was reduced and production and income were increased. The annual economic benefits for the five most important crops (papaya, mulberry, cassava, tomato and eggplant) were very high (Myrick et al. 2014).

As in the case of the cassava mealybug biocontrol program in Africa two decades earlier, farmers and consumers in the state of Tamil Nadu, India benefited greatly from the papaya mealybug biocontrol program. The economic significance of the program illustrates the importance of early identification of a new invasive insect pest and the high value of international cooperation among scientists and government agencies in initiating a biocontrol program when warranted. Local scientists knew they had a pest problem but did not recognize the pest in its early stage because it was exotic. Existing on-going international IPM cooperation saved Indian farmers and consumers at least $121 million in the first year alone. Benefits over 5 years of more than $524 million are a strong testament to the high value of international research collaboration (Meyrick et al. 2014) (See: Norton et al. in this volume).

Biodiversity is fundamental to the functioning of food webs and is the foundation of ecosystem services that are fundamental to human well-being (Savary et al. 2012). With respect to insect pests, the ecosystem service that crop-based agroecosystems provide prevent herbivores from multiplying and becoming serious pests. Two functional groups of biological control agents, predators and parasitoids, provide these services. The employment of "ecological engineering" is a procedure to enhance the activity of these naturally occurring predators and parasitoids. Ecological engineering is defined as "the integration of ecology and engineering that utilizes natural enemy sources as the predominant input to manipulate and control environmental systems" (en.wikipedia.org/wiki/ecological-engineering). Ecological engineering has been recommended as a strategy to restore biodiversity and ecosystem services for pest management in rice landscapes (Heong 2011; Gurr et al. 2012), both floral and faunal species, so that resources such as shelter and food are enhanced.

Conserving natural habitats that serve as homes for natural enemies is one component of the ecological engineering approach. Rice farmers in Thailand and the Philippines are told that they should not spray waste areas such as rice levees (bunds) with herbicides, as *Brachiaria* grasses are the homes of two cricket species that are ferocious predators of pest eggs laid on the rice leaves (Heong 2011). Also, many predacious spider species depend on these grassy habitats.

Cultural Practices

The employment of cultural practices, such as rotating with a non-host crop, intercropping, timing planting, spacing plants, tilling, managing fertilizer, managing water, etc., suppress plant pathogens, insect pests and weeds (Michel et al. 1997). Soil borne pathogens such as *Ralstonia solanacearum*, the causal agent of bacterial wilt in a number of crops including tomatoes, is difficult to manage once they invade fields. However, AVRDC studies showed that *R. solanacearum* intensity significantly declined when the previous crops were non-hosts or were left to fallow, and the incidence of tomato bacterial wilt was correlated with the remaining pathogen level (Michel et al. 1996). Research in Sub-Saharan Africa has shown that ***rotation*** with nitrogen-fixing legumes can improve soil conditions and reduce the impact of the parasitic weed, *Striga hermonthica* on subsequent cereal crops (Nwilene et al. 2008). Striga suppression was greatest in crop rotation schemes in which Striga-tolerant maize varieties were followed by soybean, cowpea or groundnut.

The Tomato yellow leaf curl virus (TYLCV), with origins in the Old World, is spreading globally. The introduction of a ***host-free period***, along with the planting of early maturing hybrids, allowed the recovery of a decimated tomato industry in the Dominican Republic (UC Davis 2002). This strategy has now been implemented in Mali by UC Davis Virologist Bob Gilbertson and has been credited with an increase in tomato production.

Chemical

The extensive use of conventional insecticides has resulted in the development of pest resistance to insecticides, outbreaks and resurgence of secondary pests, harmful pesticide residues, direct hazards to pesticide applicators and adverse effects on the environment and biological control agents (Khondaram et al. 2010; Lim 1990). This has led to the search for bio-rationale or "low risk" insecticides and biopesticides.

Biopesticides

Their crucial role in vegetable IPM strategies should be noted, as they are compatible with other pest management tactics such as natural enemies, resistant varieties, etc. (Srinivasan 2012). Biopesticides are derived from natural materials, such as animals, plants, bacteria, viruses and fungi. Biopesticides can be divided into three groups: (1) Microbial pesticides (bacteria, viruses, fungi), (2) Botanical pesticides (e. g. neem, *Azadarachta indica* and China berry, *Melia azedarach*) and (3) Biochemical pesticides (pheromones and plant volatiles).

(A) **Microbial pesticides**

1. **Bacteria**- Microbial pesticides from the soil borne bacterium *Bacillus thuringiensis* (Bt) are among the most widely used groups of biopesticides. One of the most successful examples of microbial biopesticide use is in the management of the diamondback moth, *Plutella xylostella*. This is one of the most destructive pests of vegetables in the world, sometimes causing more than 90 % of crop loss (Iqbal et al. 1996). Pesticides have been the predominant control for several decades (Syed 1992). Due to the extensive use of pesticides on vegetable brassicas, the beneficial effect of natural enemies was negated. AVRDC led the development of the IPM program for the diamondback moth in the late 1980s. Application of the biopesticde Bt resulted in excellent control, and the reduction in pesticide use dramatically decreased the cost of production and enhanced human health (AVRDC 1993). After the adoption of IPM by vegetable farmers, insecticide application was reduced by 51 % in Indonesia, 86 % in the highlands of Malaysia and 61 % in the Philippines.
2. **Viruses**- Entomopathogenic viruses, especially nuclear polyhedrosis virus (NPV) and granulovirus, are effective against various vegetable pests. *Helicoverpa armigera* NPV (HaNPV), *Spodoptera litura* NPV (SlNPV) and *S. exigua* NPV (SeNPV) have been commercialized and are widely used against the tomato fruitworm (*H. armigera*), common armyworm (*S. litura*) and the beet armyworm (*S. exigua*) respectively (Kumari and Singh 2009).

3. **Fungi**-Entomopathogenic fungi play a vital role in tropical vegetable IPM programs. *Beauveria bassiana* and *Metarhizium anisopliae* constitute about 68 % of the entomopathogenic fungi-based microbial pesticides (Faria and Wraight 2007). Although extensive research on entomopathogenic fungi has been conducted, they have not been widely commercialized and have not had a significant impact in the battle for food security as compared to *B. thuringiensis*.

(B) **Botanical pesticides**

Among the botanical pesticides, neem (*Azadirachta indica*) is widely used in vegetable IPM programs, and several formulations containing the active component azadirachtin are commercially available (Srinivasan 2012). A synergistic action of neem with the microbial pesticides such as NPVs of the tomato fruit worm (Senthilkumar et al. 2008) and entomopathogenic fungi (*B. bassiana*) against the common armyworm (Mohan et al. 2007) was reported. AVRDC has developed IPM strategies for tomato and vegetable soybean, involving neem as an integral component with microbial pesticides such as *B. thuringiensis* and NPVs in the management of phytophagous insects (Srinivasan 2012).

(C) **Biochemical pesticides**

Insect sex pheromones have long been used as monitoring and trapping tools in IPM strategies. AVRDC has developed and promoted an IPM strategy based on sex pheromones for managing eggplant fruit and shoot borer (EFSB), *Leucinodes orbonalis* in South Asia (Alam et al. 2006). The adoption of this IPM strategy led to a 70 % reduction in pesticide use in Bangladesh. The IPM strategy reduced pesticide abuse in eggplant production systems and enhanced the activity of the natural enemy *Trathala flavoorbitalis*. The mean level of *T. flavoorbitalis* parasitism increased threefold (from 10 % to 40 %) in the absence of pesticide sprays. If this level of parasitism can be sustained over large areas, it will reduce the pest population on a sustainable basis, thus reducing the need for pesticide in controlling the EFSB (Alam et al. 2003). This would be a significant achievement in the promotion of food security, increasing farm income and reducing hunger and rural poverty, as some non-IPM eggplant farmers in Bangladesh make up to 50 or more pesticide applications per cropping season, often without achieving effective and economic EFSB control (Miller et al. 2005). In fact, in eggplant-intensive growing regions of Bangladesh, 60 % of farmers apply insecticides more than 141 times in a single growing season (Rashid et al. 2003). In spite of insecticide application, more than one-third of eggplant production in Bangladesh is lost due to EFSB damage.

Resistant Varieties

World agriculture has been able to meet the rapidly growing demand for food, feed and fiber over the last half century, due to sizeable agricultural productivity growth (FAO 2009). However, growth rates of cereal yields have slowed down notably in many countries and for major commodities. In particular, the growth rates of cereal yields have been falling since the Green Revolution years. One of the prerequisites for global food security is an enhancement of investment in sustainable agricultural production (FAO 2009). This includes a need for an emphasis on the breeding of high yielding crop varieties with resistance/tolerance to the abiotic (temperature extremes, drought and flooding) and biotic stresses (phytophagous insects, plant pathogens, weeds, nematodes and vertebrates).

Where Will the Increase in Agricultural Productivity Come from?

Here we need to heed the advice of the "Father of the Green Revolution," Norman Borlaug (Braun 2011). "*Future food-production increases will have to come from higher yields. And though I have no doubt yields will keep going up*, *whether they can go up enough to feed the population monster is another matter. Unless progress with agricultural yields remains very strong*, *the next century will experience sheer human misery that*, *on a numerical scale*, *will exceed the worst of everything that has come before*."

A major component in increasing yields is to minimize the effect of pests and diseases. The employment of crop varieties with resistance to pests and diseases is an economically effective and an environmentally and ecologically sustainable approach to increasing crop yields. Genetic resistance is recognized as one of the oldest strategies of plant pest control (Islam and Catling 2012). The Greek, Theophrastus observed differences in disease susceptibility among crop varieties in the third century BCE.

The incorporation of pest resistance into modern crop varieties is a major objective of most plant breeding programs in the tropics. Resistant/tolerant varieties are important to food security for several reasons (Heinrichs et al. 1985).

- They serve as an alternative to pesticides and come without the disadvantages (cost, human health effects, environmental contamination, negative effects on natural enemies, etc.) that pesticides have.
- Varietal resistance is compatible with other control tactics-chemical, biological and cultural control. In fact, resistance enhances the effectiveness of some predators and parasitoids.
- No knowledge is needed by farmers to employ this tactic.
- Resistant varieties provide pest control at essentially no cost to the farmer.

The use of pest-resistant cultivars is a key building block in the foundation of a durable IPM program (Nicholas et al. 2011). This is well exemplified in rice IPM, in which numerous varieties with resistance to insects and diseases have been bred, using conventional breeding techniques, and commercialized on a wide scale. New technologies, including marker-assisted selection (MAS) methods, quantitative trait loci (QTL), analysis of complex genetic traits and improved plant transformation methods (biotechnology), are helping to speed up the process of getting new pest-resistant crops to the global market (Nicholas et al. 2011).

Modern agricultural biotechnology is one of the most promising developments in modern science. When used in collaboration with “traditional” or conventional breeding methods, it is a powerful tool in the fight against poverty and should be made available to poor farmers and consumers (Pinstrup-Andersen and Cohen 1999). It can raise productivity, increase resistance to pests and diseases, develop tolerance to adverse weather conditions, improve the nutritional value of some foods and enhance the durability of products during harvesting, storage and shipping (Pinstrup-Andersen 2001). The most common insect control strategy using biotechnology involves the use of the Bt gene in maize. Genetically modified crops are engineered to produce Bt toxins, a crystal protein naturally synthesized by the bacterium *Bacillus thuringiensis*. Herbicide-resistant crops are engineered to be resistant to glyphosate, an herbicide with relatively low toxic levels that allows for the spraying of glyphosate on crops to kill weeds.

The European corn borer, a widespread crop pest, claims 7 % of the world’s corn supply each year. Planting of Bt corn (maize) has saved Iowa and Nebraska (USA) farmers alone up to $1.7 billion in fighting this pest over the past 14 years, when compared to planting non-Bt varieties (Hutchinson et al. 2010). A reduction of 13 million kg of pesticide in the USA has been recorded in soybean and corn fields in the 1997–2009 time period, after the introduction of genetically modified (GM) crops (Phipps and Park 2002). Some estimates indicate that if 50 % of maize, oilseed rape, sugar beet, and cotton grown in the EU were GM varieties, pesticide use in the EU per year would decrease by 14.5 million kg of formulated product, and there would be a reduction of 7.5 million hectares sprayed. This would result in a reduction of 73,000 tons of atmospheric carbon dioxide (Phipps and Park 2002).

In spite of the advantages of GM crops, little modern biotechnology research is taking place in or for developing countries. Most such research is being conducted by private companies in industrialized countries to meet the needs of farmers in those countries. It is essential that agricultural biotechnology research is made relevant to the needs of farmers in developing countries and that the benefits of that research are transmitted to small-scale producers and consumers in those countries at affordable prices (Pinstrup-Andersen 2001).

IPM Technology Transfer and Adoption: Role in Food Security

Participatory IPM research, through its involvement of farmers, marketing agents and the public, is designed to facilitate diffusion of IPM strategies (Rajotte et al. 2005). However, widespread adoption requires careful attention to a host of factors that can spell the difference between a few hundred farmers adopting IPM technologies locally and millions adopting it over a large area. A number of strategies have been implemented over time in efforts to accelerate diffusion of IPM globally. These strategies include working with traditional public extension agencies and relying on private and not-for-profit entities that use a variety of specialized training and technology transfer methods.

Farmers fail to adopt IPM (or any technology) for three reasons (Rajotte et al. 2005): (1) The technology is not available, (2) They are unaware of the technology or unaware that it will help them or (3) The technology is unsuitable for their farm due to economic risk factors or other reasons. While the second reason is the primary basis for public support of technology-transfer programs, all three reasons can influence the appropriate design of the technology-transfer system and the ease with which IPM technologies spread from one geographical area to another.

Technology Availability

The major reason farmers fail to adopt IPM is that IPM solutions are not available for their specific pest/crop/location even if it is available elsewhere. Also, many extension services throughout the world employ extension agents who are constrained by lack of available technologies. While the fault for IPM's lack of spreading is often placed at the feet of extension, in many cases there are extension agents in villages who would be willing to extend IPM knowledge if it existed.

Awareness of Available Technology

Because farmers are numerous, diverse, broadly dispersed and understand the need for some technologies more readily than others, multiple technology transfer methods may be required to cost- effectively reach desired audiences with the adequate depth of knowledge.

The "silver bullet" technology transfer method is yet to be discovered. However, the "Farmers Field Schools" (FFS) have been one of the most attractive approaches to transfer IPM technology (Davis 2006). Farmers may be aware of a technology but choose not to adopt it because they are not aware of its net benefits. One reason that the field school approach is attractive is that it helps farmers explore some of the benefits and costs of various technologies.

Intensive training, such as that employed in the FFS approach, can be very effective with small groups, but difficult to multiply to broader audiences (Feder et al. 2004a, b). Because of the cost of training one farmer ($40–$50) it has been suggested (Rajotte et al. 2005) that the most effective use of field schools may be to train technology transfer agents who in turn will train the farmers. It is also recommended that in all cases, mass media, IT, mobile phones, demonstrations and field days, be used to disperse IPM technology to as broad an audience as possible.

Technology Suitability

Regardless of how strong the IPM technology transfer program is and how forcefully a technology is recommended, adoption of an IPM technology will not occur if it is unsuitable for a specific environment (Rajotte et al. 2005). Profitability or risk may be related to level and variability of yield or import costs, but many agro-ecological, institutional, and personal factors determine suitability of the technology.

Technology suitability is often not black and white. Farmers may adopt only part of an IPM package, not because they want to jump in slowly, but because only part of the package meets the needs of their situation. Adoption and impact assessment studies have focused on defining IPM adoption first, as adoption is frequently a matter of degree (Rajotte et al. 2005).

IPM Technology Transfer: Searching for the "Holy Grail"

The key issue regarding IPM technology transfer is how to cost-effectively spread IPM to a global audience of millions of farmers in enough depth so that they will adopt IPM in an appropriate manner. The availability, awareness and suitability of IPM technology, are only a few components in "appropriate plant protection" for providing food and environmental security in the battle against hunger. It is evident that no existing IPM technology transfer approach is a "silver bullet." Davis (2006) in her commentary, *Farmer Field Schools*: *A Boon or Bust for Extension in Africa*? concluded that what is needed is not a "one size fits all" approach, but rather local solutions for local problems. Davis, in summarizing, states that "farmer field schools are indeed a boon to extension. They have shown promise in terms of participatory methods, environmental consideration, empowerment, and productivity gain. However, it is doubtful that the FFS can be applied across the board as mainstream extension. It is not a 'quick fix' or an easily implemented solution to farmers' problems, but is another tool in the toolbox that may be appropriate to specific conditions in specific communities." FFS's are not necessarily an alternative to existing systems, but certain principles of FFS could be incorporated into existing (and novel innovative) systems to make them more effective at reaching small and marginalized farmers and in alleviating poverty. So where are we on the path to developing the silver bullet or finding the "Holy Grail" for IPM technology transfer? As aptly suggested by Davis (2006), "IPM practitioners need to identify and report the approaches that are now working and those that are not working so that we can fix them and design vigorous yet participatory research that can tell us what works when, where, how and why; and also how to scale up the approaches. It is when we use the right tools at the right place and time that pro-poor extension and true development—occur."

Hope for the Future

Dr. Norman E. Borlaug, 1970 Nobel Prize Laureate and Father of the Green Revolution, saved more humans from starvation than any other person in history. He led a lifelong battle and remained committed to the concept of global food security and a vision to provide food for the poor and reduce poverty. His commitment is expressed in the following quote:

> ***I personally cannot live comfortably in the midst of abject hunger and poverty and human misery***, ***if I have the possibilities of–even in a modest way***, ***with the help of my scientific colleagues–of doing something about improving the lives of these many young children***. (**NORMAN E. BORLAUG**)

Dr. Gordon Conway in his book, *The Doubly Green Revolution*: *food for all in the 21st Century*, wrote that "The Green Revolution (GR) proved that poverty and hunger could be alleviated through the application of modern science and technology and, without it, the number of poor and hungry today would be far greater" (Conway 1999). In Asia, the GR began with IRRI's release in the 1960s of IR8, the first modern high-yielding semi-dwarf variety. Since then, the global rice harvest has more than doubled, racing slightly ahead of population growth (Cantrell and Hettel 2004a). Poor and well-to-do farmers have benefited directly through more efficient production that has led to lower unit costs and increased profits and has significantly reduced rural poverty. Poor consumers have benefited indirectly through lower food prices. Without doubt, the "miracle rice" has brought national food security to China, India, Indonesia and other Asian countries. However, the job started in the GR is far from finished.

Although the GR did stave off hunger to a significant extent, it was limited primarily to rice and wheat in Asia, and an estimated 900 million persons still do not have access to sufficient food to meet their needs (NAS 2000). According to Conway (1999), the original GR produced new technologies for farmers, therefore creating food abundance. A second transformation of agriculture—utilizing advances in molecular and cellular biology and developments in modern ecology—is now required. He referred to this revolution as the "Doubly Green Revolution" (DGR) that stresses environmental conservation as well as crop productivity (Conway 1999). The DGR must fill the gaps existing in the GR. The DGR must go considerably beyond rice, wheat and maize and beyond Asia to Africa.

In their promotion of the DGR and Global Food Security, the Future Harvest Centers of the CGIAR have proposed an Environmental Agenda that targets seven key environmental areas. IPM plays a major role in all seven of these environmental areas:

- Poverty and the environment
- Farm chemicals and residues
- Land use and degradation
- Water use and quality
- Biodiversity

- Climate change
- Use of biotechnology

IRRI has jump-started the DGR in rice. IRRI scientists have been contributing to the DGR by looking at novel ways to manage rice pests and diseases, all with the aim of reducing—and in some cases even eliminating—chemical use. To illustrate the environmentally friendly strategies that promote food security, we discuss four IRRI projects with NARES partners in China, Vietnam, Bangladesh and other Asian countries.

Crop Biodiversity to Manage the Rice Blast Fungus

Crop biodiversity is playing a key role in helping farmers protect the environment and their families' health. Scientists have identified the benefits of planting traditional rice varieties alongside high-yielding GR varieties to manage the devastating rice blast fungus, a disease that can cost the rice industry millions of dollars per year, while at the same time reducing pesticide applications. This technology spread from 15 ha in 1997 to 43,000 ha in 2000 (Leung et al. 2003).

The results were dramatic. In the mixed varieties (traditional and HYV), blast incidence dropped to a mere 5 % from an average 55 % observed in the HYV monoculture (Zhu et al. 2000). Farmers reported an astounding US $280 more income per hectare compared to growing HYVs in a monoculture. The New York Times described the project as the "largest agricultural experiment ever with stunning results" (Yoon 2000). In 2004, farmers across ten Chinese provinces were interplanting about one million hectares, according to the lead IRRI scientist, Dr. Tom Mew.

Genetic Resistance to Rice Blast

In a search for durable resistance to rice blast pathogens, scientists are sequencing the rice genome by setting up an "allele mining" operation at the International Rice Research Institute Genebank. It is estimated that more than 91,000 distinct accessions carry a wide range of untapped traits for varietal improvement. IRRI is using genomics tools to find new genes and mechanisms to provide a broad spectrum and durable resistance to rice pathogens such as the devastating rice blast. Breeders have incorporated five known blast defense genes into a rice cultivar from China and are experiencing promising results across locations, presumably because of durable resistance to multiple races of the pathogen.

Misuse of Pesticides

Globally, hundreds of millions of farmers in the developing countries continue to overuse pesticides, despite the new IPM strategies (IRRI 2003b). While it has not been easy to wean rice farmers from their dependence on chemicals, IRRI researchers have achieved notable success in Vietnam (IRRI 2000). The project first clearly identified the damage caused by misapplied insecticides, which destroy insect predators, resulting in pest resurgence and outbreaks (IRRI 2003a). Second, they developed innovative and effective ways to communicate important scientific information to farmers (Cantrell and Hettel 2004b).

Research showed that spraying during the first 40 days after sowing was not necessary, so farmers were told that it was a waste of money and environmentally harmful through a unique and innovative communication campaign. The campaign involved local radio dramas and soap operas across the Vietnam Delta. The radio campaign was supported by leaflets, posters and billboards (Cantrell and Hettel 2004a). This unique approach persuaded almost two million rice-growing households in the Mekong Delta to cut back on the use of harmful and unnecessary pesticides. Intensive surveys indicated that insecticide use halved from an average of 3.4 applications per farmer, per season, to 1.7 applications.

In a similar campaign in Bangladesh, more than 600 rice farmers indicated that there were no significant differences in grain yield between the farmers' practices of spraying, and yields of farmers' fields that received no pesticide applications (Cantrell and Hettel 2004a). IRRI scientist Gary Jahn indicated that more than 2000 trained farmers reduced their insecticide use by 99 %. Jahn further stated that "we are hopeful that project benefits will ripple and radiate across Bangladesh's rice fields in what could be a major battle won in the Doubly Green Revolution."

"Food for All" in the Twenty-First Century

In summary, thanks to scientific advances, providing "Food for All" in the twenty-first century may be a possibility. The DGR of Conway and the "Evergreen Revolution" as per M. S. Swaminathan (Father of the Indian Green Revolution) and the Green Revolution 2.0 (GR2.0) as described by IRRI Director General Robert Ziegler, have demonstrated this potential. But the focus of this effort must go considerably beyond rice, wheat and maize and beyond Asia, North America and South America, to Africa to meet the world's growing food security needs and face the parallel challenges of improving nutrition and reducing poverty under a changing global climate. The science-based Green Revolution, referred to as the Doubly Green Revolution, is underway, tapping into the ongoing revolution in genetics, molecular biology, plant physiology, modern ecology and information technology. "Appropriate plant protection technology" is playing a vital role in the struggle for food security. In this respect, the quote of the Father of the Green Revolution is appropriate.

> *The only way that the world can keep up with food production to the levels that are needed with a growing world population is by the* ***improvement of science and technology****, and with the* ***right policies that permit the application of that science and technology*** *.* (**NORMAN E. BORLAUG**)

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Chapter 2
IPM Packages for Tropical Vegetable Crops

Rangaswamy Muniappan, E.A. Heinrichs, and Amer Fayad

Abstract This chapter describes the contrasting differences in the evolution of integrated pest management in developed and developing countries and the current status of IPM in developed countries relative to that of the developing countries. IPM in developed countries that has evolved over the past 50 years has digressed and now emphasizes control with the application of pesticides and pesticide resistance management. In contrast, IPM in developing countries emphasizes avoidance via cultural control, physical control, host plant resistance, botanical pesticides, biopesticides, behavioral manipulation, landscape management, conservation of natural enemies and biological control. The IPM packages consisting of the above technologies are detailed. The effective IPM technology transfer approach as developed by the IPM Innovation Lab is explained.

Keywords IPM packages • Package of practices • Plant protection • Pest management • Technology transfer • Vegetable IPM

Introduction

Integrated Pest Management (IPM) is a dynamic program specific to crop, location, and season that combines all available, compatible tactics to help grow healthy plants. It is a system that imparts profit, safeguards environmental and human health, encompasses cultural sensitivities, and ensures social acceptance. There are several definitions of IPM that in general include these same characteristics (Ehler 2006; Kogan 1998). IPM has been well accepted by scientists, extensionists, environmentalists, policy-makers and the public. It has been rising in stature in the

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global arena for over half a century. However, there are several misconceptions in understanding its philosophy, structure, implementation, dissemination, adoption, and evaluation among scientists and practitioners. This has led to several studies that present reasons for its poor adoption and even some skepticism as to its efficacy (Parsa et al. 2014; Zalucki et al. 2009). Fallacies in understanding IPM are often compounded in analyses of implementation and evaluation. This chapter discusses those fallacies and presents IPM packages that have been developed for tropical vegetable crops and have been adopted by farmers as alternatives to pesticides.

Development of IPM for Individual Pests

IPM is a term designed for the management of insect pests, diseases and weeds in a crop or cropping system and not a term for managing individual pests. IPM programs developed for individual pests such as the diamondback moth (*Plutella xylostella*) and tomato fruitworm, (*Helicoverpa armigera*) (Visalakshmi et al. 2005; Reddy and Manjunatha 2003; Mahmudunnabi et al. 2013; Eusebio and Morallo-Rejesus 1996) which coexist with other pests in a crop, could be selectively identified as a *component*(*s*) of an IPM package, rather than presented as complete IPM strategy, for a particular pest. The co-existence of pests and diseases requires integration of their respective management tactics in a cropping system in order to be successful. For example, an IPM program that is developed for the diamondback moth that incorporates the introduction of exotic parasitoids, without considering the management of coexisting pests such as the cabbage cluster caterpillar (*Crocidolomia pavonana*), the oriental cabbage worm (*Hellula undalis*), the tomato semilooper (*Chrysodeixis chalcites*), the flea hopper (*Halticus tibialis*) or others (Muniappan et al. 2012) in cruciferous cropping systems in the tropics, would result in the elimination of the parasitoids by the use of chemical pesticides to control these other pests.

Tactics developed for the management of *P. xylostella* should be combined with tactics developed for other pests and diseases in the IPM packages of cruciferous crops. Similarly, *H. armigera*, a polyphagous pest attacking several crops, requires integration of its management tactics into the IPM package of each crop wherein it is a pest. Zalucki et al. (2009) cited the use of pheromones for mating disruption and control of oriental fruit moth and codling moth in Victoria, Australia to be a successful IPM activity. They also stated that the introduction of parasitoids to control exotic invasive pests fit in “squarely in the ‘real’ or ‘strategic’ school of IPM.” They have identified mating disruption in one case, and classical biological control in another, as IPM, without considering other pests, diseases and weeds in the system. Even though IPM began as classical biological control and host plant resistance, and eventually saw the addition of host plant diversification and conservation biological control, it is basically an agroecological approach to pest and disease management (Pretty et al. 2010). Successful classical biological control programs for cassava mealybug (*Phenococcus manihoti*) (Neuenschwander 2003), papaya mealybug (*Paracoccus marginatus*) (Myrick et al. 2014), cassava green mite (*Mononychellus tanajoa*) (Yaninek and Hanna 2003) and weeds like giant sensitive plant (*Mimosa diplotricha*), and parthenium (*Parthenium hysterophorus*) (Muniappan et al. 2009) should be considered as components of IPM rather than designated as IPM by themselves. Classical biological control of the American serpentine leafminer, *Liriomyza trifolii*, in different parts of the world has given satisfactory results only when pesticides are not used in the fields, as the leafminer itself is resistant to pesticides but not the parasitoids introduced for its control. Thus, classical biological control is a component of IPM as is augmentative biological control. Conservation biological control is an integral part of IPM.

IPM Is for More Than Insect Pests

IPM is meant to encompass all pests (arthropods, diseases, and weeds) that attack a crop or cropping system; it does not represent the management of a single group of arthropods or diseases. However, IPM research has been dominated by an insect bias, with diseases in second place and weeds third (Pretty et al. 2010). See Zalucki et al. (2009) for a discussion of the future of IPM in Australia, and several descriptions of non-inclusive IPM. In this report, authors discuss IPM that was developed for insects attacking *Brassica* in southeast Queensland and citrus in central Queensland; and IPM that was developed for the management of an individual pest, *Helicoverpa*, in eastern Australia. In these case studies, diseases of citrus and brassica were not included. The case study on the management of *Helicoverpa* in cotton systems in Australia also falls short and cannot be considered as IPM as it does not involve other pests and diseases. Way and van Emden (2000) also dealt only with insect pests and did not include diseases in their effort to identify paths for the successful application of IPM for crops in temperate and tropical countries.

IPM Technology Transfer

The Training and Visit (T&V) extension system proved to be the popular extension program in the 1960s and 1970s when IPM first started to emerge. However, this program was ineffective in transferring IPM technologies to farmers in developing countries (Matteson 2000). In the late 1980s, FAO introduced Farmer Field Schools in Indonesia and other Asian countries. This methodology was based on participatory experimental learning to help farmers develop their analytical skills, critical thinking and creativity, as well as help them learn to make better decisions (Braun et al. 2000). It placed greater emphasis on the management of agro-ecosystems and on educating farmers concerning natural enemies in the field. However, it was weak in addressing diseases, weeds and other aspects of management. This program worked as long as expatriate scientists were involved in the farmer field schools and recommended appropriate technologies to be adopted at the right time for pest management. It was not cost-effective (Feder et al. 2004), however, as pest management reverted to the insecticide treadmill at the termination of externally-funded projects. The claim for successful implementation of IPM in Indonesia after the banning of 57 broad-spectrum insecticides—orgnophosphate, pyrethroid, and chlorinated hydrocarbon, for example—by a presidential decree in 1987 was also based on management of the brown planthopper of rice (Kogan 1998). Here, too, the discussion on IPM was based on one insect pest with little or no mention of other insect pests, mites, diseases, or weeds.

IPM Is Location-Specific

One should not expect that programs developed in the U.S. or other developed countries can be adopted in developing countries like India (Peshin et al. 2009), Uganda, or Indonesia or vice versa without modifications or adaptive research under local conditions. Most technologies developed under temperate conditions are not suitable or applicable under tropical conditions in developing countries for climatic, economic, and social reasons. Scientific capacity in most developing countries is weak and lacking in sophisticated technologies such as weather-driven computer models and the application of geographical information systems (GIS) in IPM technology transfer. Farmers in developing countries growing multiple crops in a small field lack knowledge in identifying arthropod pests and their natural enemies and diseases. They are also not in a position to understand and offer economic injury level and economic threshold level methodologies to undertake interventions, and any attempts to do so under their current conditions may not yield desired results.

IPM in Developed and Developing Countries

The science and technology for the development and implementation of IPM in developed countries began about 50 years ago. It led to the adoption of IPM principles as shown in the pyramid (Fig. 2.1a) with a base largely made up of major essential components, pest monitoring in the middle part and pesticide resistance management at the top (Steve Naranjo pers. comm.). However, in recent years the pyramid has been turned upside down (Hokkanen 2015) resulting in application of chemical pesticides and resistance management to be a major basal part and the essential IPM components to a minor role at the tip (Fig. 2.1b). This change and reversal shows the evolution of IPM in the developed countries, with an added concentration on the basic components of IPM in early stages of evolution and later gradually drifting towards pesticide resistance management. The emphasis placed on pest monitoring, development of economic threshold levels, decision support

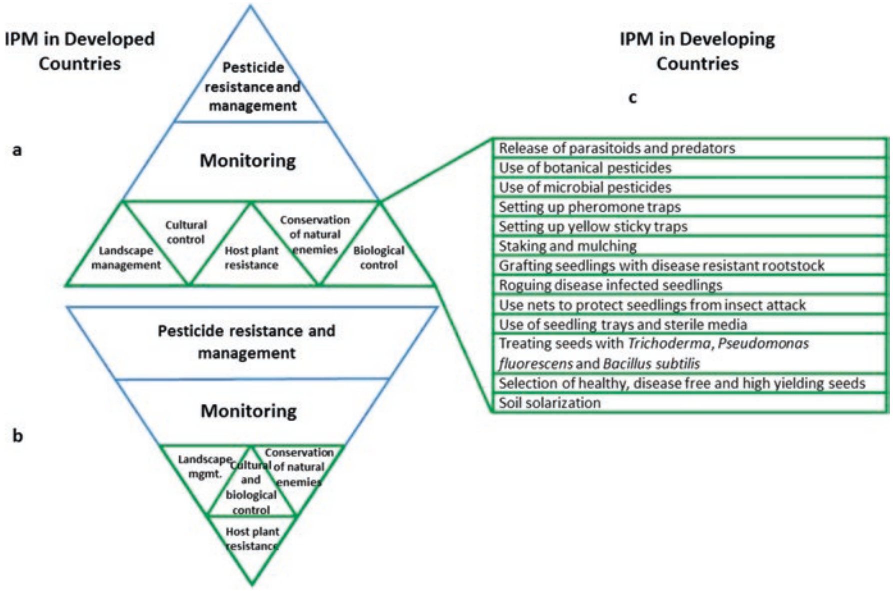

Fig. 2.1 IPM in developed and developing countries

systems, identification and registration of pesticides for a particular pest and crop, and the influence of chemical pesticide industries have led to increased use of chemical pesticides in the large scale and mono-cropped farms of the developed countries. Eventually pesticide resistance management has become a major part of IPM.

In contrast IPM did not originate and develop in the developing countries but was introduced from developed (industrialized) countries about 30 years ago, when it was considered to be the best option for crop protection at the time. Most developing country scientists were trained in the developed countries on IPM principles, technologies, and practices. Most attempts were made to directly transfer the technologies with little or no adaptive research and the principles and technologies developed for large scale farming did not fit the local conditions, resulting in expressions such as, IPM is knowledge- and skill- intensive, technology heavy (Peshin et al. 2009), poor adoption rate, weaknesses inherent within IPM (Parsa et al. 2014) and others when referring to IPM. In the developing countries, farmers have a low level of education and most farming operations are small scale with multiple crops. Pesticide registration and enforcement vary from nil to minimal in western standards. The strength and depth of IPM knowledge vary among developing countries. Some technology-heavy components of IPM established in developed countries could be readily introduced to some developing countries, but not to others. In some countries farmers apply whatever chemical pesticide is available in their nearby store, and application of an insecticide for control of a bacterial or fungal disease is not uncommon.

Based on the past two decades of experience in the developing world, the IPM Innovation Lab, a USAID funded program at Virginia Tech, has taken an approach

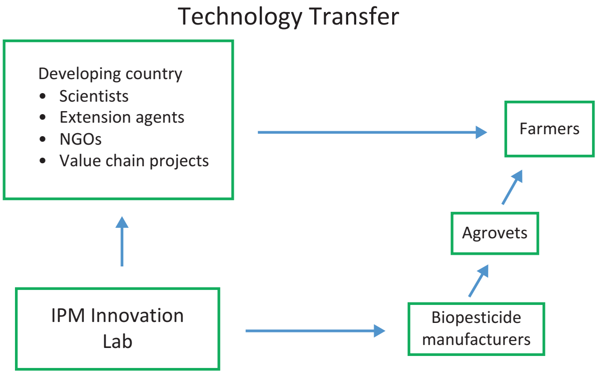

Fig. 2.2 Technology transfer

of developing IPM packages (Fig. 2.1c) for selected crops and to introduce them to farmers in collaboration with the local scientists, NGOs and others. The components developed and/or adapted are less knowledge intensive and modified to suit the local conditions. As far as technology transfer, all available avenues have been utilized to reach farmers in a given country, such as extension services, NGOs, and value chain projects (Fig. 2.2). One major constraint to the adoption of IPM in developing countries by farmers who received information/training on IPM components is the fact that they were not able to obtain the recommended products, such as *Trichoderma* spp. or other biopesticides, in the vicinity of their villages. When we encountered this problem in Nepal, we worked with agrovets to promote access and distribution and with private entrepreneurs for the production of *Trichoderma*. We provided training to entrepreneurs in production and quality control, and to agrovets on the benefits and use of bio-products (Fig. 2.2). This led to privatization of the technologies, development of a market for the products, and a sustainable technology transfer. We intend to extend and apply this approach to other developing countries as well.

IPM Packages

The IPM packages of the IPM Innovation Lab are holistic and include the development of alternative technologies to use of chemical pesticides. These technologies replace the use of synthetic pesticides for problems faced by farmers in developing countries from the time of preparing fields through the planting of seed on up through harvest. This approach does not preclude the use of pesticides when no alternative technologies are available.

An IPM package consists of stacking up technologies that will control the pests, diseases and weeds of a crop from the time of soil preparation to harvest. These include:

1. Solarization of seed beds and fields for the control of weeds, nematodes and certain pathogens;
2. Incorporating compost treated with *Trichoderma* in the soil, applying neem cake to control nematodes, and the use of vesicular-arbuscular mycorrhiza (VAM) to improve the uptake of nutrients;
3. Selecting seeds of high-yielding, locally preferred and disease-resistant varieties and treating them with *Trichoderma* spp., *Pseudomonas fluorescens*, and *Bacillus subtilis*;
4. Raising healthy seedlings using plastic trays and coco-peat, and protecting seedlings from insect pests by covering them with screens and netting;
5. Roguing of disease-infected seedlings in the nursery and in field and controlling insect pests such as thrips that pass through the netting with bio-pesticides;
6. Grafting scions of desired varieties on disease-resistant rootstock, especially for tomato and eggplants to overcome bacterial wilt disease;
7. Mulching fields to conserve moisture, and staking to prevent fruits from touching the soil in vegetable crops;
8. Adoption of augmentative, classical and conservation biological controls;
9. Use of pheromone traps to monitor pests and the application of mating disruption technologies; and
10. Incorporation of microbial and botanical pesticides into the system.

Conclusion

IPM is a successful program that needs to be promoted throughout the world, especially in developing countries, where environmental problems are rampant. It is effective, economical, socially acceptable, environmentally safe, and sustainable, provided it is designed and implemented taking into consideration the climate, economics, and knowledge status of each country involved. IPM should address problems faced by farmers in raising their crops from planting to harvest rather than only focusing on a single pest of interest of the scientist involved. IPM is dynamic and its components will change as we face climate change, the invasion of exotic species, changes in cultural practices, the development of pesticide-resistant species, and the introduction of new and novel technologies. Dissemination of information, acceptance and adoption by farmers does take time and just a few farmers adopt most of the components of a package, while some use a few components and the majority use one or a couple of components. Evaluation of IPM should not target adoption of a complete package by farmers, but it should take into account the number of components adopted.

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Chapter 3
Virus Diseases of Tropical Vegetable Crops and Their Management

Sue A. Tolin and Amer Fayad

Abstract Viruses have long been known to be prevalent in plants in tropical and sub-tropical developing countries, particularly in staple crops such as cassava, rice, coconut and pulses. The need to address a wider range of vegetable crops was identified by the IPM-Innovation Lab. To meet these needs, a team of virologists was organized to work across countries and regions with IPM specialists to document virus disease problems in priority crops; mainly tomato and peppers, melons and various gourds and cucurbits, locally preferred vegetables such as eggplant (brinjal), okra (bhendi) and yardlong bean, and fruits (passion fruit, tree tomato). These crops constitute important sources of income and food sources, for many farmers, and were observed to be infected by a wide diversity of viruses. Demands for increased production, increased uniformity of vegetables grown for domestic and export markets, changes in production practices leading to scale up of production of seeds and seedlings, changes related to intensification and global climate change, and greater crop uniformity across regions, appear to be associated with crop losses due to viruses. This chapter summarizes more than two decades of research results to identify problems, and describes progress to enhance local capacity for in-country diagnosis and implementation of integrated disease management practices.

Keywords Virus management • Virus diagnosis • Resistance • Seed-borne • Virus-vector • Host-free period • Roguing • Clean seed and seedling • Capacity building

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Viral Disease Research in the IPM Collaborative Research Support Program (CRSP) and IPM Innovation Lab (IL)

Early participatory appraisals by the IPM CRSP host countries of the four initial regional sites in Phase I (1993–1998) recognized diseases believed to be caused by viruses or virus-like agents as farmers' problems in target vegetable crops. In Jamaica, the lead country of the Caribbean Site, an aphid-transmitted virus of a non-traditional export crop, hot pepper (*Capsicum chinense*, var. Scotch Bonnet), was identified as *Tobacco etch virus* (TEV; Genus Potyvirus), (McGlashan et al. 1993) which could not be controlled by insecticides to kill aphid vectors. Therefore, unsustainable production practices were associated not only with insect pests, but also with viruses that were transmitted by the insect pests. Furthermore, insecticides destroyed natural enemies of a broad mite pest whose feeding damage resembled symptoms caused by TEV. Expertise on viruses was brought into the project from Virginia Tech faculty late in Phase I. In Phase II (1998–2004), research on TEV and vector identification, and strategies for management of this virus disease were conducted in collaboration with the Caribbean Agricultural Research and Development Institute (CARDI) (McDonald et al. 2003a, b, 2004). Near the end of Phase II, special funding to begin using biotechnology to develop virus resistant papaya and tomato was awarded to the Central America Region collaborators: University of Georgia (UGA) and University of Arizona (UA) virologists and host country institutions, University del Valle de Guatemala (UVG), Fundación Hondureña de Investigación Agrícola (FHIA), and Escuela Agrícola Panamericana Zamorano. A request from the West Africa Region for assistance with severe tomato virus problems in Mali was addressed by adding expertise from University of California-Davis (UC-Davis).

In Phase III of the IPM-CRSP (2004–2009), the sub-award category of Global Themes to work across all Regional Sites was opened for proposals and two awards were funded. The first, "Collaborative Assessment and Management of Insect Transmitted Viruses – ITV", was led by Virginia Tech and focused on aphid- and whitefly-borne viruses in the Caribbean (Dominican Republic, Jamaica), Central America (Guatemala, Honduras), and West Africa (Burkina Faso, Mali). The second, "Integrated Management of Thrips-borne Tospoviruses in Vegetable Cropping Systems in South Asia and Southeast Asia Regions", was led by Washington State University (WSU). An additional global theme, The International Plant Diagnostic Network, collaborated with ITV scientists in diagnosis of viral diseases, thus extending expertise on viruses into several regional sites.

In Phase IV (2009–2014), the two global themes merged to form the International Plant Virus Disease Network (IPVDN), "Toward the Effective Integrated Pest Management of Plant Disease Caused by Viruses in Developing Countries: Detection and Diagnosis, Capacity Building and Training, and Formulation of IPM Packages". The IPVDN was led by Virginia Tech, with US virologists from UA, UGA, UC Davis, and WSU participating in various regions and activities. At its peak, the IPVDN initiated and led activities in 19 countries of the 6 regional sites of the IPM-CRSP. The scope of the project allowed the US collaborating virologists a uniquely global view of viruses in tropical vegetable and specialty crops, and provided access to IPM researchers for inclusion of virus management in IPM packages. The project also enabled host country scientists the opportunity to meet and network with the team in workshops, and to meet other scientists within their region and across regions at sponsored workshops and at national and international scientific meetings.

The need for additional research on the TEV-induced losses in yield and marketable pepper fruit and similar problems in other crops were recognized and integrated into other programs by assembling US virologists that could work as a team, on common virus problems, across several crops and countries.

Diagnostic Approaches and Their Changes with Molecular Technology Development

Identification of viruses in samples of a crop, such as tomato, were accomplished using a battery of available immunological methods such as ELISA (enzyme linked immunosorbent assay) kits for common RNA viruses known to infect that crop. Agdia, Inc. (Elkhart, IN, USA) was often the commercial source of the tests, particularly for countries in Central America, South America and the Caribbean. Agdia's Immunostrip® Test was also widely used for RNA viruses (Fig. 3.1). For DNA viruses the methods – hybridization of radioactively labeled nucleic acid probes to "squash blots" of infected plant parts onto nylon were employed.

The two decades of virus research in the IPM CRSP/IL coincided with unprecedented advances in molecular and bioinformatic technologies for viral nucleic acid detection and sequence analysis to identify the viruses that infect plants and the classification of isolates and strains. Trans-border movement of samples to collaborators' labs for the purpose of making identifications required permits from USDA-APHIS. Later, the IPVDN team was at the forefront of adopting nitrocellulose membranes for tissue blot immunnoassays (Chang et al. 2011), and also FTA® cards (Leke et al. 2007; Naidu et al. 2013) and absorption strips and for trapping viral nucleic acids of high integrity. Begomovirus genome segments and satellites could be amplified and sequenced, then cloned and agroinoculated to observe their ability to induce virus symptoms. Bacterially-synthesized immunogenic coat proteins facilitated production of virus- and genus-specific antibodies for ELISA detection of begomoviruses and potyviruses. A broader range of immunodiagnostic reagents and services became available commercially. The challenge was to perform diagnostic procedures in host countries with limited laboratory capacity and supplies, and few trained scientists.

Fig. 3.1 Workshop participants practicing virus diagnostic techniques: (**a**) Tissue blot immunoassays at Tamil Nadu Agricultural University, Coimbatore, India. (**b**, **c**) Agdia immunostrips in the field at Nepalgunj, Nepal. (**d**) Workshop participants practicing ELISA. NARC, Kathmandu, Nepal

Virus Identification: A Critical Precursor to Successful IPM

Developing and implementing IPM approaches for the management of virus diseases in a crop first requires identification of the viruses and vectors or other means of transmission. Based on the name of the virus genus and the species, virologists use published and on-line information to predict the plant species that it might infect, its means of natural dissemination by insect vectors, and the likelihood of seed and contact transmission. The immediate challenges were assembling information about what viruses were present. A crop-specific baseline listing of viruses reported to infect solanaceous and cucurbitaceous vegetable crops was developed from published and web-based reports, and updated as new and emerging viruses were documented.

Solanaceous vegetables. Viruses from eight viral genera and one viroid genus are known to infect one or more of the solanaceous crops grown widely in the IPM IL countries e.g. tomato, pepper and eggplant (Fig. 3.2). This illustrates the complexity of identifying the diverse viruses in these crops. All three crops are infected by viruses classified in two genera, *Tospovirus* and *Begomovirus*. Tospoviruses are transmitted by several species of thrips, such as *Thrips tabaci*, *Thrips palmi*,

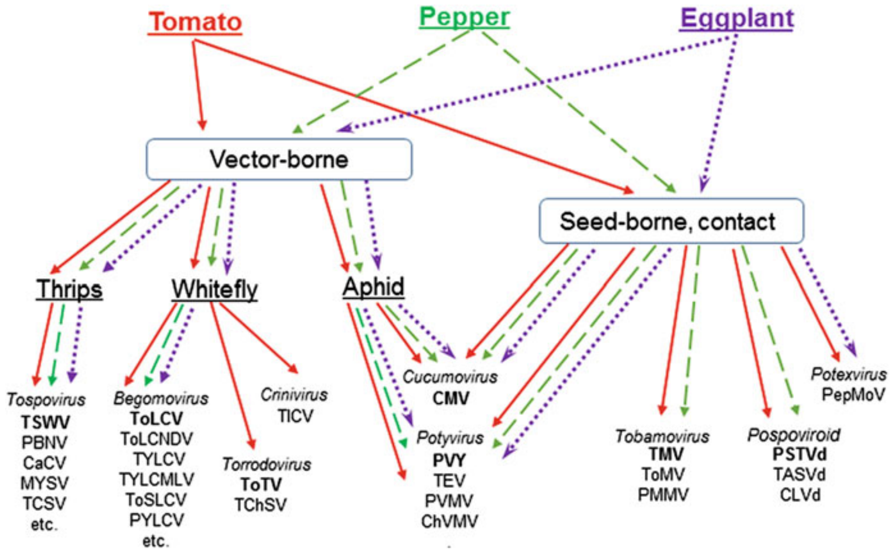

Fig. 3.2 Viruses and viroids in IPM-IL countries infecting the solonaceous vegetables tomato, pepper, and eggplant, grouped by means of transmission, vector, and viral genus. Refer to acronyms in Tables 3.1, 3.2, 3.3, 3.4, 3.5, and 3.6 for full name of each virus and viroid

Frankliniella fusca, *Frankliniella occidentalis*, and *Frankliniella schultzei* (Riley et al. 2011). It is likely that more naturally infecting viruses have been detected in tomato than in any other single crop plant. Just among the begomoviruses, there are 82 recognized begomovirus names that begin with the word "tomato", 40 beginning with Tomato leaf curl, and 10 with Tomato yellow leaf curl (Brown et al. 2015). Many of these viruses also infect pepper, even though pepper has its own suite of viruses (Kenyon et al. 2014). Fewer viruses have been described in eggplant, because it is not as widely grown outside of Asia and it's viral diseases not been as widely investigated. Begomoviruses are transmitted by whitefly vectors, mainly the whitefly *Bemisia tabaci* (sibling species), also known as the sweet potato, tobacco, or silverleaf whitefly (Gilbertson et al. 2015). Whitefly-transmitted viruses are not sap transmissible, but cloned DNA of geminiviruses and associated satellite DNA is infectious by agroinoculation. Whiteflies, including *Trialeurodes vaporarium*, are also vectors of viruses of the *Torradovirus* genus (Verbeek et al. 2014), known to infect only tomato, and of the *Ipomovirus* genus. An ipomovirus, *Eggplant mild leaf mottle virus*, is not included in Fig. 3.2 because it has not been detected in any of the IPM-IL countries. Similarly, a flea beetle-transmitted virus, *Eggplant mosaic virus* (Genus *Tymovirus*) is not included.

Aphids are vectors of viruses in the *Potyvirus* and *Cucumovirus* genera that infect these three solonaceous crops, and have a non-persistent/stylet-borne relationship with little vector species specificity. There are over 170 viruses classified as potyviruses, challenging the 288 begomoviruses for the genus with the greatest number of viruses (Brown et al. 2015). Seven distinct potyviruses, plus two identified only to genus were identified in solonaceous crops in most countries of the IPM-IL. The potyvirus *Eggplant green mottle virus* (EGMV), which may be a strain of PVY, is included in Fig. 3.2, although it was isolated from eggplant in Nigeria (Ladipo et al. 1988a, b; Sadeghi et al. 2008). Genetic resistance to potyviruses has been widely used in non-pungent *Capsicum annuum* peppers, which possess a complexity of R genes that match with virus pathotypes. *Cucumber mosaic virus* (CMV), a globally distributed virus and the type species of the *Cucumovirus* genus, has a wide host range and is seed-transmitted in pepper and other host plant species. Several strains of CMV are recognized, and are found naturally infecting these three solanaceous species. *Eggplant mottle virus*, (genus *Tymovirus*), the only virus described on solanaceous crops that is transmitted by beetles – a flea beetle (*Epitrix* sp.) – has not yet been described in developing countries.

Viruses of the genera *Tobamovirus* and *Potexvirus*, and viroids (small naked RNA) of the *Pospoviroid* genus, are contact-transmitted and seed-borne, but have no known biological vector (Fig. 3.2). These pathogens, and most aphid transmitted viruses, can be transmitted by rubbing sap extracts or purified virus onto other plants. This process is used to demonstrate that the isolate can reproduce symptoms observed in the field, and is thus the causal agent of the disease.

Cucurbitaceous Vegetables Viruses from nine genera have been associated with diseases of cucurbit vegetables (Fig. 3.3), six of which are the same as those infecting solanaceous vegetables (Fig. 3.2). Only three viruses, the tospovirus

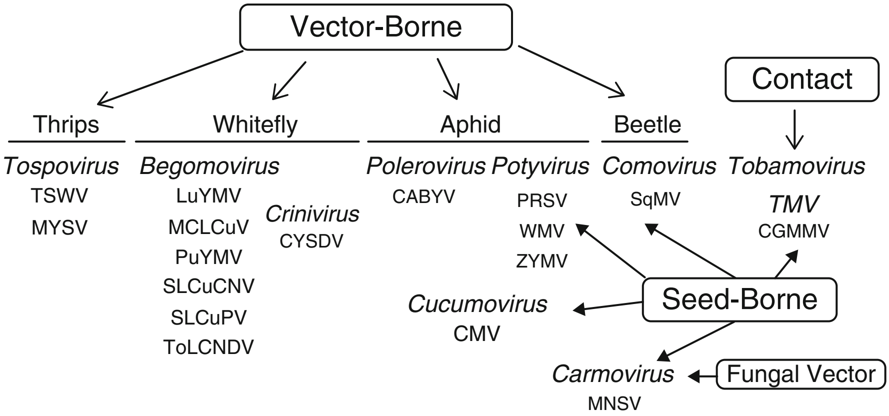

Fig. 3.3 Viruses in IPM-IL countries infecting cucurbitacious vegetables, grouped by means of transmission, vector, and viral genus. Hosts include cucumber, melon, pumpkin, squash, gourd (ash, bitter, bottle, snake, wax, etc.). TSWV *Tomato spotted wilt virus,* MYSV *Melon yellow spot virus,* LuYMV *Luffa yellow mosaic virus,* MCLCuV *Melon chlorotic leaf curl virus,* PuYMV *Pumpkin yellow vein mosaic virus,* SLCuCNV *Squash leaf curl China virus,* SLCuPV *Squash leaf curl Philippines virus,* ToLCNDV *Tomato leaf curl New Delhi virus,* CYSDV *Cucurbit yellow stunting disorder virus,* CABYV *Cucurbit aphid-borne yellows virus,* PRSV *Papaya ringspot virus,* WMV *Watermelon mosaic virus,* ZYMV *Zucchini yellow mosaic virus,* CMV *Cucumber mosaic virus,* SqMV *Squash mosaic virus,* CGMMV *Cucumber green mottle mosaic virus,* MNSV *Melon necrotic spot virus*

Tomato spotted wilt virus (TSWV), the begomovirus *Tomato leaf curl New Delhi virus* (ToLCNDV), and *Cucumber mosaic virus* (CMV) infect crop plant species in both host plant families. The three potyviruses, *Papaya ringspot virus* (PRSV), *Watermelon mosaic virus* (WMV), and *Zucchini yellow mosaic virus* (ZYMV) in Fig. 3.3 are frequently detected in squash and other cucurbits in West Africa and Asia regions, including in plantings being grown for hybrid seed production, and are distinct from all of the potyviruses in Fig. 3.2. None of the IPM IL diagnostic efforts reported detecting the fungal transmitted virus, which is also seed-borne.

The viruses and viroids that are seed-borne have increased in prevalence and importance with the global changes in production practices hybridization, grafting, production of seedlings in glass and plastic houses, and global distribution of seed by multi-national companies appear to be factors associated with this increase. Production of tomato and pepper in greenhouses protects them from aerial vectors, namely whitefly and aphids, but provides a favorable environment for thrips. Plant manipulation requiring contact spreads virus to adjacent plants. Tobamoviruses can survive and spread in circulating irrigation water in greenhouses. Seed transmitted viruses are increasingly being monitored by phytosanitary and biosecurity agencies (Rodoni 2009). In workshops held by the IPM IL, the onus has been placed on the developing country that produces hybrid seed to assure that the virus is absent in seed lots. However, IPM IL scientists observed that some of these countries have little capacity to conduct these diagnostic tests (Anggrani and Hidayat 2014).

Documenting Viruses Associated with Diseases of Vegetables Crops

The main crops targeted by the IPM IL were those that were grown in temperate climates as well as sub-tropical and tropical countries, mainly tomato, chili and other hot peppers, cucumber, pumpkin, squash and other cucurbits. In later stages of the project, crops extended to include crops of native preference for consumption such as eggplant, okra and various gourds (bitter, bottle, ridge, snake) in India, passion fruit in Kenya and Uganda, tree tomato in Ecuador, and the tropical legumes yardlong bean in Indonesia and country bean in Bangladesh. Common weedy plants in ecosystems surrounding diseased fields were also examined and found to be reservoir hosts for the virus found on adjacent crops (Leke et al. 2012a; Melgarejo et al. 2014).

Many of the viruses in Figs. 3.2 and 3.3 were detected by IPM IL collaborating scientists at all sites. Comprehensive lists of viruses and viroids, the hosts from which they were isolated in the regions and countries in which the IPM IL had active efforts and projects are shown in Tables 3.1, 3.2, 3.3, 3.4, 3.5, and 3.6. The tables include information on viruses detected in weeds and additional crops, including passion fruit, cotton, okra, legumes (yardlong and country bean, mungbean, common bean, cowpea), potato, tree tomato, and Chinese cabbage. Viruses in sweet potato grown in Central America were examined, but are not included. Each listing is from an identification conducted by US and Host Country scientists working with or trained by the Virus and Diagnostic Global Themes of the IPM IL and associated projects of the Regional Programs. Much of the information has appeared in Annual Reports of the IPM CRSP and IPM IL over a span of years (www.oired.vt.edu/ipmil) and reported at scientific meetings as oral presentations or posters.

Diagnoses were generally from samples of symptomatic plants of priority crops and not from a survey of a crop within a country. Some systematic surveys were conducted in countries where funds were available from Host Country Missions or other sources. The listing of viruses in annual reports may only be indicative of a positive ELISA test for some RNA viruses. Membrane-based sample collection was used extensively for tissue blot immunoassay (Chang et al. 2011) and nucleic acid binding on FTA cards (Bagewadi et al. 2014; Leke et al. 2007; Naidu et al. 2013), as well as on nitrocellulose membranes (Martinez et al. 2014). Identification of begomoviruses was based on DNA sequence of part or all of the genome, and in some cases was followed up by biological tests. The genus-specific immunological tests were widely used, especially for Potyviruses and Tospoviruses, and provided results from which management approaches could be designed and validated, regardless of the species. However, exact identification to virus and/or strain required additional sequence analysis of viral RNA. At least two methods of identification, often including nucleotide sequencing, were used, for validation of any virus having a peer-reviewed publication cited in the tables. These reports range from finding a common virus in a new host as e.g. CMV in eggplant (Table 3.1), to extending a virus to a new host or geographic area, occurrence of seed-borne viruses (Table 3.2), and describing a new virus genus, such as *Torradovirus* (Table 3.5).

Table 3.1 Begomoviruses and RNA viruses in the South Asia and Central Asia Regions

Virus species	Acronym	Host	References
India			
Begomoviruses			
Ageratum enation mosaic virus	AEV	Ageratum (weed)	
Cotton leaf curl Bangalore virus	CLCuBV	*Crotons sparsiflorus* (weed)	Annual Report (2014)
Malvastrum yellow vein virus	MYVV	*Malvastrum coromandelinum* (weed)	Annual Report (2014)
Bhendi yellow vein mosaic virus	BYVMV	Okra	Annual Report (2006)
Bitter gourd yellow vein virus[a]	ToLCuNDV-IN	Bittergourd, ash gourd, bottle gourd	Annual Report (2013)
Squash leaf curl China virus	SLCCNV	Bittergourd, wax gourd	Annual Report (2013)
Squash leaf curl Philippines virus	SLCuPV	Bittergourd	Annual Report (2010)
Pepper leafroll virus[a]	PeLRV	Pepper, tomato	

(continued)

Table 3.1 (continued)

Virus species	Acronym	Host	References
Tomato leaf curl Karnataka virus[1]	ToLCKV	Tomato, cucurbit	
Tomato leaf curl New Delhi virus	ToLCuNDV	Eggplant	Pratap et al. (2011)
Tomato yellow leaf curl virus	TYLCV	Tomato, pepper	
RNA viruses			
Cucumovirus: *Cucumber mosaic virus*	CMV	Cucumber, eggplant	Annual Report (2011)
Ilarvirus: *Tobacco streak virus*	TSV	Okra	Annual Report (2008)
Potyvirus: *Zucchini yellow mosaic virus*	ZYMV	Snake gourd	Nagendran et al. (2014a)
Papaya ringspot virus	PRSV	Cucurbit	Annual Report (2014)
Potyvirus genus		Pumpkin, tomato	
Tobamovirus: *Cucumber green mottle mosaic virus*	CGMMV	Snake gourd	Nagendran et al. (2014b)
Tospovirus: *Capsicum chlorosis virus*	CaCV	Pepper	Kunkalikar et al. (2007)
Peanut bud necrosis virus	PBNV	Tomato	Annual Report (2006)
Watermelon bud necrosis virus	WBNV	Melon	Annual Report (2007)
Nepal			
Begomoviruses			
Ageratum enation mosaic virus	AEV	Ageratum (weed)	Annual Report (2014)
Bhendi yellow vein mosaic virus	BYVMV	Okra	Annual Report (2014)
Tomato leaf curl virus	ToLCV	Tomato, potato	
Tomato leaf curl New Delhi virus	ToLCNDV	Tomato	Annual Report (2014)
Potyvirus: *Chili veinal mottle virus*	ChVMV	Tomato, pepper	Annual Report (2010)
Bean common mosaic virus	BCMV	Yardlong bean, cowpea	
Papaya ringspot virus	PRSV	Papaya	Annual Report (2010)
Zucchini yellow mosaic virus	ZYMV	Pumpkin, squash, gourds	Annual Report (2010)

(continued)

Table 3.1 (continued)

Virus species	Acronym	Host	References
Bangladesh			
Begomoviruses			
Tomato leaf curl virus	ToLCV	Tomato, pepper	Annual Report (2007)
Tomato leaf curl Joydebpur virus	ToLCJV	Pepper	Annual Report (2013)
Tomato leaf curl New Delhi virus	ToLCNDV	Tomato, cucurbit, pepper	Annual Report (2010)
Bhendi yellow vein mosaic virus	BYVMV	Okra	Annual Report (2007)
Mungbean yellow mosaic India virus	MYMIV	Mungbean, yardlong bean	Annual Report (2014)
Pumpkin yellow vein mosaic virus[a]	PYVMV	Bitter gourd, pumpkin	Annual Report (2014)
RNA viruses			
Cucumovirus: *Cucumber mosaic virus*	CMV	Eggplant, cucumber	Bagewadi et al. (2014)
Potyvirus: *Bean common mosaic virus*	BCMV	Yardlong bean	Annual Report (2012)
Papaya ringspot virus	PRSV	Ash gourd, bottle gourd	Annual Report (2011)
Watermelon mosaic virus	WMV	Sponge gourd, ridge gourd	Annual Report (2010)
Zucchini yellow mosaic virus	ZYMV	Squash, snake gourd	Annual Report (2011)
Tobamovirus: *Cucumber green mottle mosaic virus*	CGMMV	Cucumber	Annual Report (2007)
Tajikistan			
Potyvirus: *Bean yellow mosaic virus*	BYMV	Bean	Annual Report (2013)
Potato virus Y – NTN	PVY	Potato	Alabi et al. (2012)
Tospovirus: *Iris yellow spot virus*	IYSV	Onion	Annual Report (2014)

[a] Virus names not italicized are not on the ICTV list of approved virus names (Brown et al. 2015)

Table 3.2 Begomoviruses and RNA viruses in the Southeast Asia Region

Virus species	Acronym	Host	References
Indonesia			
Begomoviruses			
Mungbean yellow mosaic virus	MYMV	Melon, yardlong bean	Annual Report (2014)
Pepper yellow leaf curl Indonesia virus	PYLCIsV	Pepper, tomato	De Barro et al. (2008) and Trisno et al. (2009)
Tomato leaf curl New Delhi virus	ToLCNDV	Tomato	
Tomato yellow leaf curl Kanchanaburi virus	TYLCKaV	Eggplant, tomato	Kintasari et al. (2013)
RNA viruses			
Ilarvirus: *Tobacco streak virus*	TSV	Okra	
Polerovirus:			
Cucurbit aphid-borne yellows virus	CABYV	Cucumber	
Cucumovirus: *Cucumber mosaic virus*	CMV	Yardlong bean, cucumber, tomato, potato	Damayanti et al. (2010)
Potyvirus: *Bean common mosaic virus*	BCMV	Yardlong bean	Damayanti et al. (2010)
Chili veinal mottle virus	ChVMV	Tomato	Annual Report (2014)
Potato virus Y	PVY	Potato	Damayanti et al. (2014)
Potyvirus genus		Yardlong bean	
Turnip mosaic virus	TuMV	Chinese cabbage	
Comovirus: *Squash mosaic virus*	SqMV	Cucumber, zucchini	Annual Report (2011)
Tobamovirus: *Tomato mosaic virus*	ToMV	Tomato	Annual Report (2014)
Carlavirus: *Potato virus S*	PVS	Potato	Annual Report (2014)
Potexvirus: *Potato virus X*	PVX	Potato	Annual Report (2013)
Cambodia			
Begomoviruses			
Luffa yellow mosaic virus	LYMV	Cucumber, Ridge gourd, Ribbed gourd	Annual Report (2010)
Tomato leaf curl virus	TLCV	Cucurbits	Annual Report (2014)
Tomato leaf curl New Delhi virus	ToLCNDV	Cucurbit	
Tomato yellow leaf curl virus	TYLCV	Tomato, eggplant	Annual Report (2014)
RNA viruses			
Cucumovirus: *Cucumber mosaic virus*	CMV	Cucumber	
Philippines			
RNA viruses			
Cucumovirus: *Cucumber mosaic virus*	CMV	Bean, cucumber	Annual Report (2011)

Table 3.3 Begomoviruses, RNA viruses and Viroids in the West Africa Region

Virus species	Acronym	Host	References
Ghana			
Begomoviruses			
Sida yellow leaf curl virus	SiYLCV	Sida (weed)	
Tomato leaf curl Ghana virus	ToLCGV	Tomato	Annual Report (2013)
Tomato severe rugose virus	ToSRV	Tomato	
Viroids			
Pospiviroid: *Potato spindle tuber viroid*	PSTVd	Tomato	
Tomato apical stunt viroid	PASVd	Tomato	Annual Report (2013)
Mali			
Begomoviruses			
Sida yellow leaf curl virus	SiYLCV	Sida (weed)	Annual Report (2014)
Okra yellow crinkle virus	OYCrV	Okra	Annual Report (2007)
Cotton leaf curl Gezira virus	CLCuGeV	Cotton, okra	Annual Report (2007)
Tomato leaf curl Ghana virus	ToLCGhV	Tomato	
Tomato leaf curl Kumasi virus	ToLCKuV	Tomato	
Tomato severe leaf curl virus	ToSLCV	Pepper	
Tomato severe rugose virus	ToSRV	Tomato	
Tomato yellow leaf crumple virus[a]	ToLCrV	Tomato, pepper	Zhou et al. (2008)
Tomato yellow leaf curl virus	TYLCV	Tomato	Noussourou et al. (2008)
Tomato yellow leaf curl Mali virus	TYLCMLV	Tomato	Chen et al. (2009) and Zhou et al. (2008)
RNA viruses			
Crinivirus: *Cucurbit yellow stunting disorder virus*	CYSDV	Cucurbit	Annual Report (2008)
Cucumovirus: *Cucumber mosaic virus*	CMV	Pepper	Annual Report (2010)
Potyvirus: *Zucchini yellow mosaic virus*	ZYMV	Squash	Annual Report (2009)
Pepper veinal mottle virus	PVMV	Pepper	Annual Report (2010)
Viroids			
Pospiviroid: *Columnea latent viroid*	CLVd	Tomato	Batuman and Gilbertson (2013)
Guinea, Senegal			
RNA viruses			
Cucumovirus: *Cucumber mosaic virus*	CMV	Tomato	Annual Report (2011)
Burkina Faso			
Begomoviruses			
Cotton leaf curl Gezira virus	CLCuGeV	Cotton	
Pepper yellow vein Mali virus	PeYVMLV	Pepper, tomato	Sattar et al. (2014)
Tomato leaf curl Mali virus	ToLCMLV	Tomato	Sattar et al. (2014)
Tomato yellow leaf curl Mali virus	TYLCMLV	Tomato	Sattar et al. (2014)

(continued)

Table 3.3 (continued)

Virus species	Acronym	Host	References
RNA viruses			
Potyvirus: *Cowpea aphid-borne mosaic virus*	CABMV	Cowpea	Annual Report (2008)
Pepper veinal mottle virus	PVMV	Pepper	Annual Report (2008)
Papaya ringspot virus	PRSV	Cucurbit	Annual Report (2008)
Cameroon			
Begomoviruses		Ageratum	Leke et al. (2012a)
Cotton leaf curl Gezira virus	CLCuGeV	Cotton	Annual Report (2007)
Okra yellow crinkle virus	OYCrV	Okra	Annual Report (2007)
Okra leaf curl virus			Leke et al. (2012b)
Tomato leaf curl Ghana virus	ToLCGV	Tomato	Annual Report (2008)
Tomato yellow leaf curl virus	TYLCV	Tomato	Annual Report (2009)
Tomato yellow leaf curl Mali virus	TYLCMLV	Tomato	
RNA viruses			
Potyvirus: *Cowpea aphid-borne mosaic virus*	CABMV	Cowpea	
Passion fruit woodiness virus	PWV	Passionfruit	
Potato virus Y	PVYb	Tomato	
Tobamovirus: *Tobacco mosaic virus*	TMV	Tomato	

[a]Virus names not italicized are not on the ICTV list of approved virus names (Brown et al. 2015)

Table 3.4 Begomoviruses and RNA virus in the East Africa Region

Virus species	Acronym	Host	References
Kenya			
Begomoviruses			
Tomato yellow leaf curl virus	TYLCV	Tomato	Annual Report (2008)
RNA viruses			
Potyvirus: *Passion fruit woodiness virus*	PWV	Passion fruit	Annual Report (2006)
Cowpea aphid-borne mosaic virus	CABMV	Passion fruit, cowpea	Annual Report (2009)
Potato virus Y	PVY	Tomato	Chikh Ali et al. (2015)
Uganda			
Begomoviruses			
RNA viruses			
Cucumovirus: *Cucumber mosaic virus*	CMV	Tomato	Annual Report (2012)
Tobamovirus: *Tobacco mosaic virus*	TMV	Tomato	Annual Report (2012)

(continued)

Table 3.4 (continued)

Virus species	Acronym	Host	References
Tomato mosaic virus	ToMV	Tomato	Annual Report (2011)
Cucumber green mottle mosaic virus	CGMMV	Cucumber	
Potyvirus: *Passion fruit woodiness virus*	PWV	Passion fruit	Otipa et al. (2013)
Uganda passiflora virus[a]	UgPV	Passion fruit	Ochwo-Ssemakula et al. (2012)
Potyvirus genus		Tomato	
Tospovirus: *Tomato spotted wilt virus*	TSWV	Tomato	Annual Report (2011)
Impatiens necrotic spot virus	INSV	Tomato	Annual Report (2008)
Tanzania			
Begomoviruses			
Tomato yellow leaf curl virus	TYLCV	Tomato	Annual Report (2011)
RNA viruses			
Potyvirus: *Cowpea aphid-borne mosaic virus*	CPABMV	Cowpea	

[a] Virus names not italicized are not on the ICTV list of approved virus names (Brown et al. 2015)

Table 3.5 Begomoviruses and RNA viruses in the LAC Region: Guatemala and Honduras

Virus species	Acronym	Host	References
Guatemala			
Begomoviruses			
Pepper golden mosaic virus	PepGMV	Pepper, tomato	Palmieri et al. (2008) and Annual Report (2006)
Pepper huasteco yellow vein virus	PHYVV	Pepper, tomato	Palmieri et al. (2008) and Annual Report (2006)
Tomato leaf deformation virus	ToLDeV	Tomato	
Tomato mosaic Havana virus	ToMHV	Tomato	Palmieri et al. (2008) and Annual Report (2009)
Tomato severe leaf curl virus	ToSLCV	Tomato	Palmieri et al. (2008) and Annual Report (2006)
Tomato yellow leaf curl virus	TYLCV	Tomato, tomatillo, pepper	Salati et al. (2010)
RNA viruses			
Crinivirus: *Cucurbit yellow stunting disorder virus*	CYSDV		
Torradovirus: *Tomato chocolate spot virus*	TChSV	Tomato	Batuman et al. (2010)
Tospovirus: *Tomato spotted wilt virus*	TSWV	Pepper, tomato	Palmieri et al. (2008) and Annual Report (2012)
Potexvirus: *Potato virus X*	PVX	Potato	Annual Report (2011)
Potyvirus: *Bean common mosaic virus*	BCMV	Bean	Annual Report (2013)

(continued)

Table 3.5 (continued)

Virus species	Acronym	Host	References
Potato virus A	PVA	Potato	
Potato virus Y	PVY	Potato, tomato	Annual Report (2012)
Tobacco etch virus	TEV	Tomato	
Fabavirus: *Broad bean wilt virus*	BBWV	Bean	Annual Report (2014)
Sobemovirus: *Southern bean mosaic virus*	SBMV	Bean	
Alfamovirus: *Alfalfa mosaic virus*	AMV	Tomato	
Cucumovirus: *Cucumber mosaic virus*	CMV	Tomato	
Tobamovirus: *Tobacco mosaic virus*	TMV	Bean, tomato	Annual Report (2006)
Tomato mosaic virus	ToMV	Tomato	Annual Report (2012)
Polerovirus: *Potato leafroll virus*	PLRV	Potato	
Carlavirus: *Potato virus S*	PVS	Potato	Annual Report (2011)
Potato virus M	PVM	Potato	
Honduras			
Begomoviruses			
Bean golden yellow mosaic virus	BGYMV	Phaseolus bean	
Melon chlorotic leaf curl virus	MCLCuV	Melon, watermelon	
Pepper huasteco yellow vein virus	PHYVV	Pepper, tomato	
Pepper golden mosaic virus	PGMV	Pepper, tomato	
Tomato golden mottle virus	ToGMoV	Tomato	Annual Report (2009)
Tomato leaf curl virus	ToLCV	Tomato	
Tomato leaf deformation virus	ToLDeV	Tomato, pepper	
Tomato mosaic Havana virus	ToMHV	Tomato, pepper	Annual Report (2010)
Tomato mottle virus	TMoV	Tomato	
Tomato severe leaf curl virus	ToSLCV	Tomato, Pepper	Annual Report (2009), (2010)
Tomato severe rugose virus	ToSRV	Tomato, pepper	
Tomato yellow leaf curl virus	TYLCV	Tomato, pepper	
RNA viruses			
Cucumovirus: *Cucumber mosaic virus*	CMV	Pepper	Annual Report (2006)
Polerovirus: *Potato leaf roll virus*	PLRV	Potato	

(continued)

Table 3.5 (continued)

Virus species	Acronym	Host	References
Potexvirus: *Potato virus X*	PVX	Potato	Annual Report (2010)
Potyvirus: *Potato virus Y*	PVY	Tomato	Annual Report (2009)
Papaya ringspot virus	PRSV	Cucurbit	Annual Report (2009)
Pepper mottle virus	PeMoV	Pepper	
Tobacco etch virus	TEV	Pepper	
Watermelon mosaic virus	WMV	Melon	
Zucchini yellow mosaic virus	ZYMV	Melon	
Tobamovirus: *Pepper mild mottle virus*	PMMoV	Pepper	Annual Report (2009)
Tobacco mosaic virus	TMV	Tomato, potato, eggplant	Annual Report (2006)
Tomato mosaic virus	ToMV	Tomato	Annual Report (2007)
Tospovirus: *Tomato spotted wilt virus*	TSWV	Pepper	Annual Report (2009)

Table 3.6 Begomoviruses and RNA viruses in the LAC Region: Dominican Republic, Jamaica, and Ecuador

Virus species	Acronym	Host	References
Dominican Republic			
Begomoviruses			
Jatropha yellow mosaic virus	JMV	Jatropha (weed)	Melgarejo et al. (2014)
Tomato yellow leaf curl virus	TYLCV	Tomato	Annual Report (2006)
Tomato yellow leaf curl virus -Is	TYLCV-Is	Tomato	Annual Report (2011)
Tomato yellow leaf curl virus -Mld	TYLCV-Mld	Tomato	Kon et al. (2014)
RNA viruses			
Cucumovirus: *Cucumber mosaic virus*	CMV	Pepper	Annual Report (2007)
Potyvirus: *Tobacco etch virus*	TEV	Pepper	Annual Report (2007)
Tospovirus: *Tomato spotted wilt virus*	TSWV	Pepper	Martínez et al. (2014)
Tomato chlorotic spot virus	TCSV	Pepper	Batuman et al. (2013b)
Tobamovirus: *Tobacco mosaic virus*	TMV	Tomato	
Pepper mild mottle virus	PMMoV	Pepper	Annual Report (2008)

(continued)

Table 3.6 (continued)

Virus species	Acronym	Host	References
Jamaica			
Begomoviruses			
Tomato yellow leaf curl virus	TYLCV	Tomato	Annual Report (2006)
RNA viruses			
Potyvirus: *Tobacco etch virus*	TEV	Hot pepper	Annual Report (2005)
Potato virus Y	PVY	Pepper	
Cucumovirus: *Cucumber mosaic virus*	CMV	Pepper	
Ecuador			
Begomoviruses			
Pepper leafroll virus	PpLRV	Pepper, tomato	Annual Report (2015)
Tobacco yellow crinkle virus	TbYCV	Tomato, melon, passionfruit. papaya	Annual Report (2014)
Tomato leaf deformation virus	ToLDeV	Tomato	Annual Report (2012)
RNA viruses			
Potyvirus: *Papaya ringspot virus*	PRSV	Melon, watermelon	Annual Report (2012)
Peru tomato mosaic virus	PerTMV	Tree tomato	Annual Report (2013)
Potato virus Y	PVY	Tree tomato	Annual Report (2012)
Polerovirus: *Potato leaf roll virus*	PLRV	Tree tomato	Annual Report (2014)
Cucumovirus: *Cucumber mosaic virus*	CMV	Melon, cucumber	Annual Report (2014)
Tospovirus: *Melon yellow spot virus*	MYSV	Melon	Quito-Avila et al. (2014)

Management Through IPM Approaches

Developing and implementing IPM approaches for the management of arthropod-transmitted virus diseases first requires identifying the virus (es) and vector(s) involved and secondly, developing an understanding of the biology of these viruses and their vectors in cropping systems, e.g., the host-range of the viruses and vectors including potential weed hosts. Based upon this information, an IPM approach can be proposed that involves production of virus-free transplants or seeds, implementation of regional host-free periods, planting improved varieties (either early maturing [after the host-free or low-vector period] or disease resistant), and sanitation, i.e., emphasizing the importance of removing old crops after harvest and not planting

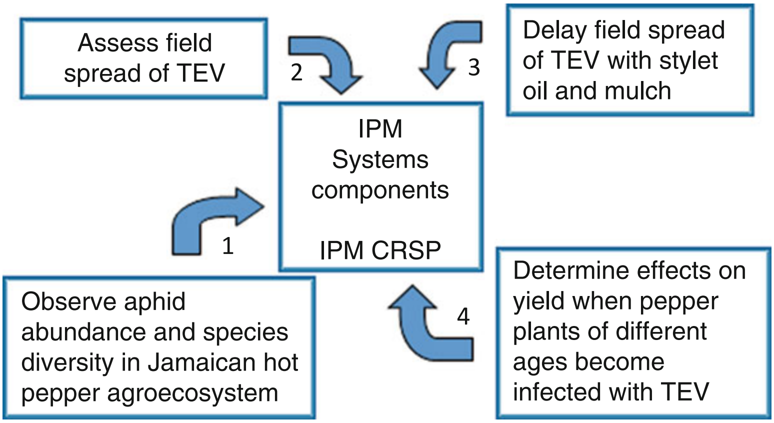

Fig. 3.4 Steps in a research program showing systems components of an IPM package to manage aphid-transmitted potyvirus in Jamaica (McDonald et al. 2003a, b, 2004)

new crops near old crops (for an example see: Salati et al. 2010; Gilbertson et al. 2011). Other strategies that may be used include roguing of infected plants (Karthikeyan et al. 2012), reflective mulches, and weed management in and around crops. Only as a last resort will management of insect vectors with insecticides be used. Some degree of success has recently been attained with the newer bio-rational insecticides. Clearly, for integrated management to be developed and applied effectively, a cropping systems approach taking into account multiple interacting factors is essential. The identification of TEV in pepper in Jamaica and the additional studies on the aphid-virus-host interactions by the IPM IL scientists (McDonald et al. 2003a, b, 2004; Tolin et al. 2007) was essential in designing a research program for an IPM approach for the management of this disease (Fig. 3.4).

A key component of IPM systems is also the development of resistant varieties, which can be achieved through various means, including plant breeding programs conducted by national and international organizations, and by private companies (e.g., seed companies). However, equally important is the establishment of field trials to screen germplasm in areas where virus pressure is high. This allows for the identification of varieties that are locally adapted, acceptable to farmers, and which are resistant/tolerant to viruses prevalent in a given area.

IPM Package

The IPM Innovation Lab has focused its efforts on designing and delivering an IPM package including a set of different components, often referred to as technologies. These will vary based on the location, crop, and time. Farmers can use one or several of the technologies in a packages depending on local conditions and availability of these components. An example of an IPM package is listed below (oired.vt.edu/ipmil)

- Choose virus resistant or well-adapted varieties
- Use of disease-free seeds, seedlings, and planting material
- Grow healthy seedlings in plastic trays with coco-peat and *Trichoderma* under net covers
- Rogue symptomatic seedlings in the nursery and subsequent roguing of infected/symptomatic plants in the field during the first 3–4 weeks after transplanting
- Remove and destroy weeds, volunteer crops, and crop residues that serve as a source of the virus or vectors
- Use appropriate crop density
- Control virus vectors by crop rotation, crop isolation, and barrier crops (Chavan 2015)
- Use reflective mulches to deter vectors

Observations on Clean Seed and Seedling Production/Managing Virus Vectors

Clean seed and seedling programs have been highlighted in workshops as being essential to successful crop production. Seed-borne viruses often build up in seeds that are saved by growers from plants infected with a potyvirus, CMV, and the stable, mechanically-transmitted tobamoviruses TMV/ToMV and viroids in tomato. Aphids are the most common vectors of seed-borne viruses, mainly potyviruses and CMV (Fig. 3.2). The wide-spread prevalence of the tobamoviruses in tomato globally (Guatemala, Uganda, Bangladesh, Nepal) suggests an increase in seed-borne virus, reduced use of resistant varieties, or/and development of new strains of virus overcoming resistance in tomato. Seed-borne viruses in peppers, melons and other cucurbits, and beans, appear to have increased in farmer-saved seed. However, our Indonesian farmers found that commercially-sold lots of yardlong bean seeds were infected with BCMV and that only 60 % of emerging seedlings emerged (Damayanti et al. 2010). Researchers in Uganda selected seed from symptomless hot peppers to develop a line for farmers that had decreased virus levels and greater seedling vigor. From initial plants, viruses can be spread mechanically (through handling during transplant, pruning, and picking).

Seed transmission has not been demonstrated with viruses that are -transmitted by whiteflies and only rarely by thrips, and not in vegetable crops. Thrips may transmit seed-borne Ilarviruses such as *Tobacco streak virus* in okra in Indonesia (Table 3.2), but most likely only mechanically via pollen movement.

Clean seedlings produced in bulk for transplant may be infected early via vectors from virus-infected abandoned fields, if not protected from the vectors, usually aphids, thrips, or whiteflies.

Understanding the virus-vector interactions is crucial in managing both the vector and the virus/virus disease. The best approach is an IPM approach based on cultural practices, biological control, and chemical control methods (Chavan 2015). This follows the same principles proposed by Zitter and Simons (1980) in controlling viruses by managing virus vectors, virus transmission by vectors, and cultural practices. Cultural practices include controlling the virus inoculum sources, vector, control, isolation from potential sources of virus and vector, isolation by time, barrier crops, interplanting, and adjusting plant density (Zitter and Simons 1980).

The success of chemical control of virus vectors depends on mode of transmission of the virus by the insect vector. Insecticides are more effective in controlling semi- and persistently-transmitted viruses and are not effective against non-persistently transmitted viruses (Lecoq and Katis 2014). Insecticides will actually increase the rate of transmission on non-persistently transmitted viruses as these pesticides increase the probing incidence and therefore potential for acquisition and transmission (Chavan 2015). Using mineral and vegetable oils can be helpful in managing virus vectors and reducing transmission of non-persistently transmitted viruses when virus inoculum pressure is low or moderate (Lecoq and Katis 2014). One adverse effect of mineral and vegetable oils is the potential phytotoxicity that depends on concentration, crop, and environmental factors (McDonald et al. 2004).

Insecticides should be used in combination with other control methods for efficient management of whiteflies and whitefly transmitted viruses. Neonicotinoids are among the most suitable chemical insecticides for controlling whitefly populations as they quickly reduce the population and therefore reduce their chance to transmit the virus. Insecticide resistance development and adverse effects on pollinators are serious concerns and a reason why several countries have banned or put forward plans to eliminate the use of neonicotinoids (Lapidot et al. 2014).

Megasari et al. (2014) reported that chitosan was effective in suppressing *Aphis cracivora* (a vector of BCMV) populations and feeding preference and lead to reduction in the BCMV titer, incidence and severity in yardlong beans in Indonesia. Chitosan (0.9 %) as a foliar application was the most effective chemical for controlling both the vector and the disease (Dayamanti et al. 2010; Megasari et al. 2014).

As a result of limitations to effective management of insects by chemical insecticides the IPM concept is a necessity. Other IPM components used to manage virus vectors include the use of row covers (cloth, net, plastic), and screen/plastic houses or tunnels (Fig. 3.5). A limitation to smallholder farmers is the additional cost and the return on investment (in Nepal, a smallholder farmer will recover cost of a 20×3m plastic tunnel after 1 year). Large growers in the LAC region have experienced virus diseases in moderately contained greenhouses with thrips-transmitted tospoviruses in pepper and tomato (Martínez et al. 2014; Batuman et al. 2013a) and with PMMoV in peppers.

Growing seedlings in plastic trays with coco-peat with or without *Trichoderma* and under net covers (Fig. 3.6) has been field tested in India and resulted in lower virus incidence in the nursery and in the field after transplanting compared to seedlings raised in nursery beds in open field nurseries (Fig. 3.7). This technology was subsequently transferred and disseminated in Bangladesh, Nepal (Fig. 3.8), and other IPM IL host countries. Another successful technology developed and disseminated by this program is roguing infected/symptomatic seedlings in the nursery before transplanting and subsequent roguing of infected/symptomatic plants in the field after transplanting. This practice was especially successful in managing thrips-transmitted PBNV in tomato in India (Naidu 2012) because it reduced the inoculum source and lowered the spread and disease incidence in the field.

Fig. 3.5 *Left* – Growing cucurbit plants under row covers in Gazipur, Bangladesh. A fine mesh is used to reduce virus vectors and other insects from damaging the crop. *Middle* and *right*: Mesh house in Salama Valley, Guatemala (tomato) to exclude whitefly vectors of begomoviruses

Fig. 3.6 Commercial nursery seedling production in Coimbatore, Tamil Nadu, India. Seeds are planted in plastic trays, using coco-peat inoculated with *Trichoderma* as the growth medium, under net covers. Yellow sticky traps and roguing are also used

Planting infected seeds poses a threat to farmers and international trade (Lecoq and Katis 2014) and use of infected seeds has been a factor for rapid and long distance spread of several virus diseases, especially in cucurbits (Lecoq and Desbiez 2008). Commercial seed companies have used disinfection (Trisodium phosphate)

Fig. 3.7 Open field tomato nursery – Coimbatore, Tamil Nadu, India

Fig. 3.8 Farmers in Kathmandu Valley, Nepal raising their seedlings in plastic trays, using coco-peat inoculated with *Trichoderma* as the growth medium, under net covers. Yellow sticky traps and roguing are also used

and dry heat (72 °C for 24–72 h) without affecting seed germination. However these treatments are not applicable in small scale seed production or where farmers produce their own seeds (Lecoq and Katis 2014). Furthermore they are effective only for tobamoviruses that contaminate the surface of the seed, and not for the embryo infecting potyviruses and CMV.

Several cucurbit viruses such as ZYMV are seed transmitted and virus symptoms occur during early stages of seedling growth and development (Figs. 3.3 and 3.9). On several field visits to Bangladesh, India, and Nepal, IPM IL scientists observed more than 90 % virus incidence in cucumber, pumpkin, and squash in the seedling stage or before flowering. The resulting virus disease can lead to severe yield loss and reduction in food and income. Saving seeds only from healthy plants or using certified hybrid seeds can be used as one IPM component, in addition to managing aphid vector populations.

Avoiding over lapping crops, especially in cucurbits and other crops that have a short growing cycle where farmers grow several consecutive crops, is crucial in reducing both the virus and vector (Lecoq and Katis 2014).

Relying on chemical pesticides for control of tomato pests is the most common control method used by farmers in Mali. However, this is not very effective against whiteflies (Nouhoheflin et al. 2007).

Fig. 3.9 Seed-borne viruses are a serious problem in cucurbit production. About 90 % of the seedlings in this field in Nepal showed virus-like symptoms. Plants tested positive for ZYMV. *Left*: Naidu Rayapati (WSU) showing farmers how to recognize virus-like symptoms in the field. *Right*: close-up of mosaic symptoms on squash

Fig. 3.10 Continuous cropping provides an inoculum source of virus and vectors to infect newly planted crops. *Left*: new tomato crop planted adjacent to older crop where leaf curl disease was detected (Kathmandu Valley, Nepal); *Right*: Women farmers planting a field of tomato adjacent to a crop infected with a thrips-transmitted virus (Coimbatore, Tamil Nadu, India)

Host free periods have been the most successful strategy for management of whitefly-transmitted begomoviruses. This requires an area-wide approach and has been successful in managing TYLCV in the Dominican Republic and Mali and saving the tomato industry in these countries (Gilbertson 2011; Noussourou et al. 2008; Palmieri et al. 2008). Since these viruses persist in the vector but do not pass to the next generation, growing plants that are not hosts to the virus allows whitefly populations to be "cleansed" of virus, thus eliminating the source of virus for new tomato crops. Impact assessment studies reported by Nouhoheflin et al. (2010) showed that combining a host-free period and virus-tolerant seeds as a component of an IPM strategy resulted in $4.8 million to $21.6 million in benefits in Mali. The benefit was divided into one third for producers and two thirds for consumers. Similar strategies could be used on a smaller scale by crop rotation and by avoiding continuous or adjacent planting of the same crop to reduce exposure to a source of virus inoculum (Fig. 3.10).

Genetic and Induced Resistance

Varietal selection and breeding for genetic resistance, if available, is an important component of an IPM Package, but has not been an activity of the IPM IL other than informational. There have been several reports of applications of biologicals including *Trichoderma* and *Pseudomonas* to reduce symptom severity and decrease losses to virus disease. The mechanism is proposed to be induction of resistance to the virus, or an increase in tolerance. Research reported from India, Indonesia (Damayanti and Wiyono 2013) and Guatemala – Annual Report 2013- suggest these approaches should be considered for IPM Packages with crops having severe virus disease problems. Several reports suggest that chitosan induces systemic resistance against viruses. Noiket et al. (2014) reported that chitosan treatment improved seed germination and growth of the tomato variety Thai Sridathip 3 and reduced TYLCV symptoms. Chitosan formulation with *Pseudomonas* sp. reduced the severity of ToLCV in India (Mishra et al. 2014).

Training and Capacity Building

The IPVDN, in cooperation with the Diagnostics Global Theme and Regional Sites, has provided training in these identification methods for scientists from many of the collaborating IPM IL host countries and for degree-seeking graduate students. The following are some of the training activities conducted in the last phases of the project. In July 2008, a week-long phytopathological diagnosis workshop in Guatemala, organized by IPVN, included more than a day of virology for participants from Central American countries and Jamaica (Fig. 3.11). During Phase IV of the IPM IL (2009–2014), the IPVDN hosted 35 training programs with the participation of 1185 people, (85 % men and 15 % women). In total, we conducted 16 workshops, 13 specialized trainings, 3 farmer meetings, 3 conferences/seminars. These were tailored to the specific needs of scientists, technicians, extension agents, students, and farmers. The IPM CRSP/IPM IL completely or partially supported more than 30 scientists/technicians in their BS, MS, or PhD degrees, in which IPVDN scientists guided their thesis/dissertation research and other activities related to virus diagnostics, virus management and IPM.

In November 2010, IPVDN organized a workshop on “Management of Viral Diseases of Vegetable Crops” in Honduras. The purpose of this workshop was to train field extension agents on virus disease management and how to integrate this into an IPM approach. About 90 participants, including more than 45 extension agents of the projects EDA-MCA and USAID-RED, the most important providers of assistance to small vegetable growers in Honduras, attended this workshop. In addition, participants included 20 field extension workers of the development agencies/projects Visión Mundial (World Vision), FUNDERH, FHIA, Global Village (Aldea Global) and PROMIPAC/Zamorano, and 15 agents representing seed companies and local distribu-

Fig. 3.11 Workshop participants in the Disease Diagnostic Workshop, Guatemala from Guatemala, Honduras, El Salvador, Nicaragua and Jamaica

tors of other agricultural inputs. Another workshop organized by IPVDN in Honduras in 2010 focused on "Potato psyllid/*Ca*. Liberibacter solanacearum, a new bacterial-insect vector complex causing diseases of potato and tomato in the Americas." The objective of the workshop was to inform professionals that the causal agent for this disease was not a virus and the focus was on psyllid, not whitefly, vectors.

In July 10–13 2012, the IPM IL and USDA sponsored a plant virology symposium entitled "Management of Insect-transmitted Virus Diseases in Vegetables in the Tropics and Subtropics," held at Tamil Nadu Agricultural University, Coimbatore, India. The main purpose of this symposium was to review the current status of insect-transmitted virus disease management in the tropics and subtropics. Plant virologists and entomologists from the U.S., India, and IPM CRSP host countries including Bangladesh, Ghana, Honduras, Indonesia, Senegal, Uganda, and Tanzania discussed the current status of research, education, and extension relevant to the management of virus diseases. Collaborating scientists focused on building multidisciplinary global expertise to address insect-transmitted virus diseases impacting agricultural sustainability and food security in developing countries. Discussions focused on emerging and re-emerging virus diseases, especially those of vegetable crops in IPM CRSP host countries, and establishing a coordinated program on identification and management of virus diseases affecting cucurbits, eggplant, okra, pepper, and tomato. A plan for future collaborative research under an IPM CRSP global theme project, the International Plant Virus Disease Network was discussed.

Participants Focused on the Need for:

- Developing standard operating procedures (SOPs) for virus identification and protocols for collecting, shipping and processing samples and validation of diagnostic test results.
- Developing local networks of experts for each IPM CRSP region
- Devising a reporting mechanism for recording incidence of plant virus diseases and evaluating host plant resistance
- Documenting the impact of virus diseases and benefits of their management to convince donors to fund R&D activities related to virus diseases in small-holder agriculture

In April 2014, the IPVDN conducted the "IPM Innovation Lab plant virus disease global theme workshop on seed-borne virus diseases of vegetable crops" in Nepal. Participants included representatives of the Department of Agriculture, Nepal Agricultural Research Council (NARC), USAID, International Development Enterprises (iDE), Knowledge-based Integrated Sustainable Agriculture and Nutrition project (KISAN), Center for Environmental and Agricultural Policy Research, Extension and Development (CEAPRED), Agrovets, Himalayan College of Agricultural Sciences and Technology (HICAST), and agricultural universities. Discussions covered the basic aspects of plant virus diseases, detection and diagnosis, epidemiology, and management. Round table discussions focused on virus diseases of cucurbits, tomato, okra, and pepper. A capacity building session tackled the needs in terms of formal education, training of practitioners, research, and extension. Participants were divided into four groups and each discussed the four categories and suggested needed strategies to build the capacity in plant virology in Nepal.

In June 2014, the IPM IL organized an "International Workshop on Seed-and-Seedling-borne Diseases of Vegetable Crops" in Hyderabad, India. This workshop was held in collaboration with the USAID mission in India and the Indian National Institute of Plant Health Management, Hyderabad. The main purpose of this workshop was to present results over time from the IPM-IL research programs, the current status of seed-borne diseases, and the role of the seed supply chain in their management.

In April 2015, the IPM Innovation Lab (IPM IL) organized a workshop on "Disease Diagnosis and Basic Plant Pathological Techniques for Early Career Scientists" that was conducted in collaboration with NARC and iDE, Nepal at the regional NARC station in Khajura, Banke (Fig. 3.12). The main objective of this workshop was to provide training on plant disease diagnosis and management with emphasis on bacterial, fungal, and viral diseases.

The participants (29 males; 4 females) of the workshop were drawn from NARC stations across Nepal, faculty and students from the Institute of Agriculture and Animal Sciences/Tribhuvan University, HICAST, Agriculture and Forestry University (AFU), and field officers from the IPM Innovation Lab-Nepal/CEAPRED. The participants studied the principles of identification, isolation, and purification of bacterial and fungal diseases, and investigated extraction and testing of botanicals against fungal diseases. A major focus was on plant virus diseases, especially those of importance to Nepal and South Asia. Topics covered basic virus

Fig. 3.12 Workshop participants, Disease Diagnosis and Basic Plant Pathological Techniques, for Early Career Scientists Khajura, Banke, Nepal

characteristics, epidemiology, and management. Special lectures and laboratory sessions addressed various aspects involved in the detection of plant viruses and the capacity to conduct these techniques in NARC. Participants received hands-on experience in identifying virus symptoms in the field, collecting samples for disease identification, and conducting serological techniques (ELISA, Immunostrips) for virus detection. This validated the fact that such diagnostic assays can be successfully conducted with minimal facilities to achieve intended results and impacts in NARC stations.

IPM IL scientists from the US contributed to the sections covering plant virus diseases and NARC scientists contributed to fungal and bacterial diseases sessions – this is an example of drawing on local expertise and supplementing it with expertise from the US to train the next generation of agricultural scientists and extension personnel for overall capacity building in Nepal. This workshop was the result of continued collaboration between IPM IL and NARC and highlights the exemplary partnership among IPM IL, NARC and NGOs like iDE and CEAPRED.

IPVDN Achievements

Highlights in Asia

- *Bean common mosaic virus* and *Cucumber mosaic virus* were associated with virus disease epidemics in yardlong beans in Indonesia. Both viruses are seed-borne and aphid-transmitted. Transfer of this technology and diagnostic methods to Indonesian scientists helped to contain the disease in subsistence agriculture.

These results were acknowledged in USAID EGAT Bureau for Economic Growth, Agriculture & Trade, vol 1.1, 2009 under the title "A team of scientists from the EGAT-managed Integrated Pest Management Collaborative Research Support Program (IPM CRSP) and Indonesia's Bogor Agricultural University identified a new virus disease that is devastating yardlong bean crops in Java, Indonesia."

- In India, capacity building in plant virology was undertaken at the Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu. Scientists at this institution are now able to identify the most prevalent plant viral diseases in their state, including discovery of newer, economically-important vegetable viruses that had not yet been reported in India.
- Farmer participatory IPM packages were implemented in Tamil Nadu for mitigating negative impacts of the thrips-transmitted *Peanut bud necrosis virus* (PBNV) on tomato production. Raising clean tomato seedlings and roguing of symptomatic seedlings during and soon after transplanting reduced virus incidence and gave economic benefits to resource-poor farmers who had previously incurred costs for spraying pesticides in unsuccessful efforts to control virus spread by thrips vectors. The IPM IL team worked collaboratively with farmers' groups and research and extension personnel in several tomato-growing regions to disseminate benefits of IPM as an affordable strategy to reduce crop losses due to PBNV and produce quality fruits for consumers (Naidu 2013).
- In Nepal, Bangladesh, Cambodia and Tajikistan, the information generated by science-based identification of viruses infecting vegetables is helping scientists learn if a virus is likely to be transmitted by seed, and whether aphids, whiteflies or thrips are the vectors. With accurate identification of viruses, NGOs and farmers can implement crop sanitation and disease management strategies benefiting poor farmers.
- Central Asian countries were found to have very little knowledge of viruses. Training was initiated by a scientist from Uzbekistan, but the program was later limited to Tajikistan. In conjunction with a training workshop to an eager audience, viruses were documented from potato, onion, and tomato, but no additional work was conducted.

Highlights in Africa

- A whitefly-transmitted begomovirus was identified as the cause of a leaf curl disease of tomato in Mali. A host-free period in which no tomato could be grown in an area for 2 months, following practices in place in Dominican Republic and Guatemala, restored tomato production in the Baguineda area.
- A complex of diverse begomoviruses and viroids have recently been identified as causes of severe leaf curl diseases and a stunting disease known locally as "rasta" in tomato in Ghana.
- Passion fruit woodiness in Uganda and Kenya is associated with potyviruses that are very closely related to *Cowpea aphid-borne mosaic virus* (Ochwo-SSemakula et al. 2012; Otipa et al. 2013). Detection methods by ELISA and PCR have been developed, and new laboratories constructed in which the tests can be performed. Management strategies have been targeted to virus-free seedlings, and educational workshops have been held for training of seedling producers (Ochwo-

Ssemakula et al. 2013). Interventions to decrease dissemination in the field by aphids are also under study.

- Tomato surveys in Uganda by ELISA detection show up to 60 % virus infection, with major incidence of TMV and ToMV in farmers' fields (Arinaitwe et al. 2013). Capacity now exists in Tanzania for additional surveys in the region to document the prevalence of begomoviruses in tomato.
- Diagnostic workshops with the Diagnostics global theme (IPDN) have been held in East (Ghana) and West (Tanzania) Africa, and SOPs (Standard Operating Procedures) have been drafted for standardized detection of TYLCV and viruses associated with passion fruit, and other viruses.

Highlights in Latin America and Caribbean Region

- Capacity building for virus identification and management – trained Universidad del Valle de Gutemala (UVG) personnel and students, joint workshops conducted by in-country and US collaborators. Three women scientists, two from Jamaica and one from Guatemala, earned graduate degrees studying viruses in the United States.
- Whitefly vector biology and diversity – two species of whitefly, *Bemisia* and *Trialeuroides*, are vector species at different altitudes and regions of Guatemala. Vector population diversity was assessed in association with the begomoviruses transmitted. Thrips were shown to be important vectors of tospoviruses in greenhouse peppers in Dominican Republic and Guatemala.
- High incidence of PVX in potato and TMV in tomato in Western Highlands of Guatemala shows the need for clean seed and seedling programs and improved sanitation practices.
- Sweet potato virus diagnostic probes have been designed and validated to enable developing seed certification activities with sweet potato in the Central America region of their origin (Avelar and Brown 2014).
- Tree tomato viruses in Ecuador were identified as PVY and *Peru tobacco mosaic virus*, both aphid-transmitted potyviruses. In Ecuador, the first survey for cucurbit viruses identified the tospovirus MYSV, which is the first report of this virus in the New World.
- In Honduras, the non-viral cause of Zebra chip of potato was identified, together with its psyllid vector. Vector phenology patterns were studied, leading to recommendations for management practices (Rehman et al. 2010).

Highlights Across Countries and Regions

- Potato viruses identified by host country scientists in Guatemala and Indonesia were the same viruses, showing the need to virus-test seed and propagules, to aid subsistence farmers whose practice of using self-saved potato as seed has led to a build-up of viruses.
- Common diagnoses of TMV and ToMV in tomato in several countries (Guatemala, Uganda, Nepal, India), and the persistence of these viruses on seed and their highly contagious nature to spread by contact, suggests the need for sanitation practices in hybridization, grafting, transplanting, and cultivation in all countries where tomatoes are intensively grown in fields and in contained houses.

- Discovery of seed-borne viruses – TSV in okra and CMV in eggplant – that pose severe threats to major vegetables grown for food in Mali and Bangladesh, and grown in Central America as oriental vegetables.
- Understanding the taxonomic status of the whitefly *Bemisia tabaci* sibling species complex in relation to begomovirus-vector interactions, and the genetic diversity of vector haplotypes in relation to the pathogen genotype, for both the whitefly and psyllid vectors in the context of changing climate and agricultural systems of tropical countries.

Top Ten Recommendations

Based on IPM IL work, and our interactions with host country scientists, extension agents, plant protection specialists, and plant protection students, discussions with plant virologists, plant protection and IPM specialists at professional meetings, USAID workshops, and professional symposia we propose the following as general recommendations to strengthen the capacity of local scientists in identification of viruses and diagnostic capabilities.

Diagnostics

1. Conduct workshops and training in host counties in house
2. Support national centers in developing diagnostic labs and methods
3. Establish centers of excellence that help with regional training, testing, and in time help transition to individual country institutions
4. Need to update overall poor laboratory infrastructure, in terms of equipment, electrical power, and skilled personnel
5. Need to standardize testing
   (a) Sampling and sample preservation
   (b) Shipping
   (c) Protocols
   (d) Validation
6. Need quick tests for field work
7. Need to develop low cost tools, kits, tests
8. Progress has been made and we should be positive and should create new systems to continue going forward
   (a) An increasing number of labs are doing good diagnostics work
9. Train extension workers, farmers, technicians on diagnostic methods, proper identification
   (a) How to interact with diagnostic labs (public or commercial)
   (b) Need effective communication

10. Every country needs to have the capability to do pest/disease diagnostics
    (a) National level
        (i) Time may be limiting to wait for results from regional labs/centers of excellence
    (b) Need certified accredited labs

Capacity Building

1. Networking, in person and virtual, and up-to-date information on people, projects, and opportunities.
2. Journal access (reading and publishing).
3. Inter-Africa collaboration between institutes (international and national programs, universities, international centers)
4. Build South-South collaborations
    (a) South-South: National partners should be at the core of the project
    (b) EU model of institutional collaboration across a region.
5. Web resources for networking literature
6. Imposed mixing of people at conferences
7. South-south communication and collaboration, especially more within Africa
8. Establish a type of "community of practice" – information and support for materials exchange (quarantine capacity)
9. International exchanges with incentives for students to return to their home countries
    - Follow-up grants
    - Policy changes
    - Study other successful models. (India, China – salaries and funding, facilities)
10. Integration/synergy of projects on common themes.

A quarter century ago Bos (1992) noted that "In the developing countries, knowledge regarding viruses and their ecology and detectability remains essential". Our recommendations mirror those suggested by Bos (1992) regarding the survey/identification of viruses and diagnostic tools/methods, understanding the ecobiology of viruses, and developing comprehensive control strategies for virus diseases in developing countries. There still exists a pressing need to train a future generation of plant virologists and plant protection specialists, especially at resource poor institutions in developing countries. The IPM IL IPVDN scientists' major paradigm shift was to train the host country participants and build their capacity and confidence in disease diagnosis and virus identification and management.

Acknowledgements This chapter covers highlights of activities of teams of scientists, and aims to integrate our experiences and results with important landmark concepts of plant virology, epidemiology, and disease management. Our thanks go especially to those scientists in the United

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Chapter 4
Exploring the Potential of *Trichoderma* for the Management of Seed and Soil-Borne Diseases of Crops

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Abstract Recent agricultural development across the globe has created a positive mindset among the stakeholders to face the predicted challenges of the changing socio-economic scenario of the current millennium. Investment in agricultural research has resulted in the introduction of several scientific innovations of commercial value in different fields of the agricultural sector, which warrants for the stakeholder partnership. Among the several commercially feasible technologies, biopesticides occupy a prime position. The export oriented agricultural and horticultural crops depend on the export of residue free produce. It has created a great potential and demand for the incorporation of the fungal antagonist *Trichoderma* and bacterial antagonist *Pseudomonas* in crop protection. To ensure the sustained availability of the antagonistic biocontrol agents at the village level, the rural centers for the manufacturing of the same must be established. The technical know-how could be shared with entrepreneurs so as to facilitate the commercial production and to ensure the availability of *Trichoderma* and fluorescent *Pseudomonas* for the farming community.

In most developing countries the scientific community does not have the technical knowledge to mass produce *Trichoderma* spp., and bacterial antagonists such as endophytic bacteria and plant growth promoting rhizobacteria (PGPR), in order to promote their use for plant growth promotion and disease control. Hence, knowledge and skill oriented training were imparted to the scientists and entrepreneurs in developing countries through the IPM-Innovation Lab. The antagonistic organisms were effective against several soil-borne pathogens offering multiple disease protection, and are now being used by the farming community to ensure sustained residue free food production by delivering the antagonists through seed and soil.

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Keywords *Trichoderma* • Seed and soil-borne diseases • Bacterial antagonists • Rhizosphere • Seed treatment • Mass production • Commercialization

Introduction

Despite the use of plant protection practices, about one third of the crops produced are destroyed by pests and diseases. The discovery of synthetic chemicals has greatly contributed to food production increase by controlling pests and diseases. However the use of these synthetic chemicals during the last three decades has raised a number of ecological and health problems. In the recent years, scientists have diverted their attention towards exploring the potential of beneficial microbes, and natural plant products for plant protection measures.

Bio-control agents e.g. *Trichoderma* spp., are safe to humans, cheaper than pesticides, highly effective throughout the crop growth period and have high rhizosphere competence and competitive saprophytic ability. The other advantages are ease of delivery, improved plant growth, activation of the resistance mechanism in the host, and increased biomass production and yield. In addition to environmental safety, development of resistance to pathogens is also minimized. These antagonists act through antibiosis, secretion of volatile toxic metabolites, mycolytic enzymes, parasitism and competition for space and nutrients. Though bio-control is an acceptable green approach, the present day bio-products can be further improved to obtain greater levels of disease reduction. Development of formulations with increased shelf life, increased bio-efficacy and with a broad spectrum of action is necessary. These improvements could still pave the way for the increased commercialization of *Trichoderma* technology and would make it a viable component in Integrated Pest Management.

Trichoderma as a Successful Bio-control Organism

Trichoderma is the most widely used biocontrol agent. Among the various isolates of *Trichoderma*, *T. viride*, *T. asperellum*, *T. harzianum*, *T. virens* and *T. hamatum* are used in the management of various diseases of crop plants. It has many advantages as a bio-control agent:

(a) High rhizosphere competence
(b) High competitive saprophytic ability
(c) Enhances plant growth
(d) Great arsenal of inducible polysaccharide –degrading enzymes
(e) Produces secondary metabolites/antibiotics of volatile and non volatile nature

(f) Ease for mass multiplication
(g) Broad spectrum of action against various pathogens
(h) Provides excellent and reliable control
(i) Environmentally safe (Jeyarajan and Nakkeeran 2000)

Identity of *Trichoderma*

Trichoderma spp. are cosmopolitan saprophytic green mold fungi that colonize the plant rhizosphere and trigger induced systemic resistance (Harman 2000). Besides, they also colonize cellulosic and decaying materials (Kubicek et al. 2009; Jaklitsch 2009). Owing to the potential of powerful hydrolytic enzymes, *Trichoderma* has also been isolated from cockroaches (Yoder et al. 2008), aquatic organisms (Sallenave et al. 1999; Sallenave-Namont et al. 2000), and from termite guts (Sreerama and Veerabhadrappa 1993).

The green conidial ascomycetous fungi belonging to the genus *Trichoderma* are soil-borne, and distributed throughout the universe. *Trichoderma*, being a soil – borne saprophyte, with increased competitive saprophytic ability and potent degradative machinery, successfully colonizes the habitats in which it dwells and out competes its competitors. The potential fungal saprophyte cum antagonist was first introduced in to the microbial world by Persoon (1794). The sexual stage of the *Trichoderma* was identified as *Hypocrea* by Tulasne and Tulasne (1865). However, using phenotypic approaches it was very difficult to distinguish between the genus*Trichoderma*/*Hypocrea* until 1969. Subsequently, Rifai (1969) and Samuels (2006) initiated studies to differentiate the species of *Trichoderma*. *Trichoderma*/*Hypocrea* produce pigments varying from colorless to bright greenish-yellow to red. Similarly, conidial pigmentation also varies from green, gray, brown and also colorless. The species identification within the genus is very difficult due to the narrow range of variation in *Trichoderma* (Gams and Bissett 1998). The Index Fungorum database (http://www.indexfungorum.org/Names/Names.asp) described the existence of 471 different species of *Hypocrea* and 165 types of *Trichoderma* which have become obsolete in the genomic era.

However, development in the field of genomics, facilitated characterization and identification of *Trichoderma* spp., using oligonucleotide barcode (TrichoKEY) and a customized search tool (TrichoBLAST) (Druzhinina et al. 2005). Both TrichoKEY and TrichoBLAST are available online at www.isth.info. Based on the molecular tools, 100 phylogenetically defined species were described (Druzhinina et al. 2006a). Besides, phenotypic microarrays have been used for the detection of *Trichoderma* spp., based on the utilization pattern of 96 carbon sources (Bochner et al. 2001; Druzhinina et al. 2006b). In recent days, based on the usage of molecular tools, 104 species of *Trichoderma* have been described by the International Sub commission on *Trichoderma*/*Hypocrea*. This is described on the website http://www.isth.info/biodiversity/index.php. Existence of 75 species of *Hypocrea* has been described in Europe by the use of molecular tools (Jaklitsch 2009).

Molecular Detection of *Trichoderma*

In recent days the identity of *Trichoderma* based on molecular approaches has been used to overcome the confusion associated with the detection and confirmation of *Trichoderma* up to genus and species level. The specific genes like actin, calmodulin, ATP citrate lyase, endochitinase, RNA polymerase 2, Translation elongation factor 1-alpha, and ITS regions can be used for the detection of *Trichoderma* spp. (Table 4.1).

Trichoderma as Rhizofungi and Opportunistic Symbiont

The plant growth promoting and mycoparasitic fungi, *Trichoderma* are capable to grow in the rhizosphere and colonize the plant roots internally as an opportunistic endo symbiont (Harman et al. 2004). It prevents the entry of plant pathogens into infection court through direct confrontation and by triggering the immunity of the

Table 4.1 Genes associated with detection of *Trichoderma*

Gene	Primer	Sequence	References
Actin	TRI-ACT1	5′ TGGCACCACACCTTCTACAATGA 3′	Samuels et al. (2011, 2012)
	TRI-ACT2	5′ TCTCCTTCTGCATACGGTCGGA 3′	
	ACT-500 F	5′ ATTCCGTGCTCCTGAG 3′	
	ACT- 511 R	5′ CTCAGGAGCACGGAAT 3′	
Calmodulin	CL1	5′ GARTWCAAGGAGGCCTTCTC 3′	
	CAL737RM	5′CATYTTTCKKGCCATCATGG 3′	
ATP citrate lyase	acl1-230up	5′AGCCCGATCAGCTCATCAAG 3′	Grafenhan et al. (2011) and Jaklitsch et al. (2013)
	acl1-1220low	5′ CCTGGCAGCAAGATCVAGGAAGT 3′	
Endochitinase	chi18-5-1a	5′GCT(CT)TCCATCGGTGGCTGGAC 3′	Kullnig-Gradinger et al. (2002) and Lieckfeldt et al. (2000)
	chi18-5-2a	5′GGAGTTGGGGTAGCTCAGC 3′	
RNA polymerase 2	fRPB2-5f	5′ GA(T/C)GA(T/C)(A/C)C(A/T) GATCA(T/C)TT(T/C)GG 3′	Liu et al. (1999)
	fRPB2-7cr	5′ CCCAT(A/G)GCTTG(T/C)TT(A/G) CCCAT 3′	
Translation elongation factor 1- alpha	EF1-728f	5′CATCGAGAAGTTCGAGAAGG 3′	Carbone and Kohn (1999)
	TEF1Rg	5′ GCCATCCTTGGGAGATACCAGC 3′	Samuels et al. (2002)
ITS region	ITS 5	5′ GGAAGTAAAAGTCGTAACAAGG 3′	White et al. (1990)
	ITS 4	5′ TCCTCCGCTTATTGATATGC 3′	

plant (Vargas et al. 2009, 2011). Triggering of immunity by *Trichoderma* via rhizosphere colonization induces changes in the secretome and proteome profiles, that results in plant growth promotion and improvement of yield parameters (Lorito et al. 2010; Brotman et al. 2012; Morán-Diez et al. 2012).

Rhizosphere Colonization and Penetration into Roots by *Trichoderma*

Interplay of signals between the host plant and *Trichoderma* spp. results in colonization of the rhizosphere region by *Trichoderma*, both externally and internally. The mechanisms associated with the primary interaction of plant and *Trichoderma* are poorly understood. However, *Trichoderma* produces growth hormones like auxins that serve as signal molecules to colonize roots and increase the surface area of colonization (Contreras-Corenjo et al. 2009). *Trichoderma* binds to the host root by producing cysteine-rich hydrophobin-like proteins like TasHyd1 from *T. asperellum* and Qid74 of *T. harzianum* (Samolski et al. 2012; Viterbo and Chet 2006). Besides, swollenin, an expansin-like protein from *Trichoderma* plays a crucial role in plant root colonization (Brotman et al. 2008).After binding on to the root, penetration into the root is mediated through the secretion of expansin-like proteins with cellulose binding modules and endopolygalacturonase by *Trichoderma* spp. (Brotman et al. 2008; Morán-Diez et al. 2009). Initial suppression of ISR may facilitate root invasion. After gaining entry into the root, *Trichoderma* spp. grow between the cells and are limited to the epidermal and outer cortex layer. However, *T. koningii* gains entry into the root of *Lotus japonicus* by suppressing phytoalexin production during root colonization (Masunaka et al. 2011). Regulation of root growth in canola by *T. asperellum* was mediated through the gene *accd* encoding ACC deaminase (Viterbo et al. 2010).

Trichoderma as Endophytes

In general, *Trichoderma* spp., colonize the roots and gain entry into the plant and perform as opportunistic symbionts. However, the *Trichoderma* of recent evolutionary origin such as *T. stromaticum*, *T. amazonicum*, *T. evansii*, *T. martiale*, *T. taxi* and *T. theobromicola* use non-root mode of entry into the plant and dwell as true endophytes (Druzhinina et al. 2011; Chaverri et al. 2011). These new evolutionary endophytes were different from routinely isolated *Trichoderma* isolates from the soil/rhizosphere. The phylogenetic analysis confirmed that these species pertain to recent evolutionary origin (Druzhinina et al. 2011; Chaverri et al. 2011). The endophytic *Trichoderma* species protect plants from diseases and abiotic stresses by inducing transcriptomic changes in plants (Bailey et al. 2006; Bae et al. 2009). Few of these endophytes colonize the surface of glandular trichomes and form appressoria-like structures (Bailey et al. 2009) and behave as endophytes.

Mode of Action

Antagonists interact with the pathogen and host in soils either directly or indirectly. In indirect interactions the plant responds to the presence of the antagonist, resulting in induced resistance or plant growth promotion.

Direct Mechanism of Action

Competition

Most of the soil-borne pathogens are controlled by the competition for space or court of infection on roots and seeds. Biological control of silver leaf disease caused by *Chondrostereum purpureum* was controlled by *Trichoderma viride* through early colonization of fresh wounds (Corke and Hunter 1979). Competition also seems to be the most potent mechanism employed by *T. harzianum* T-35 in the control of *Fusarium oxysporum*. f. sp. *vasinfectum* and *F. oxysporum*.f. sp. *melonis* in the cotton rhizosphere and melon (Sivan and Chet 1989).

Antibiosis

Antibiotics are low molecular weight (<1 kDa) secondary metabolites produced during nutrient limiting conditions. *Trichoderma* species produce more than 43 secondary metabolites which exhibit antibiotic activity. Among these compounds alkyl pyrones, isonitriles, polyketides, petaibols, diketopiperazines, sesquiterpenes, and steroids are often found to be associated with biocontrol activity.

Volatile antibiotics produced by *T. harzianum* are inhibitory to *Rhizoctonia solani* and *Macrophomina phaseolina* (Dennis and Webster 1971). The volatile metabolites effective against fungal pathogens were identified as Pentyl analogues namely 6-n-pentyl-2H-pyran- 2-one and 6-n-pentenyl-2H-pyran- 2-one. Production of volatile harzianolide by *T. harzianum* [3- (2- hydroxyl-propyl)-4 (hexa – 2″ – dienyl – 2(5H) furanone] was found to be antifungal. *T. viride* produces a number of antifungal metabolites e.g. trichodermin, dermadin, trichoviridin and sesquiterpene heptalic acid.

Gliotoxin an epidiothidiketopiperazine produced by *Gliocladium virens* G20 is a key factor in reducing damping off of Zinnia (Wilhite et al. 1994). *Gliocladium virens* pertaining to ‘Q’ group produced gliotoxin and dimethyl gliotoxin, but the ‘P’ group produced gliovirin (diketopiperazine) and heptelidic acid. Gliovirin was more inhibitory to *P. ultimum* damping-off in cotton than ‘Q’ strains, which were effective against *R. solani* (Howell et al. 1993).

The UV mutants of *T. harzianum* produce trichorzianines, which are hydrophobic peptides, interacting with phospholipid membrane and induce membrane permeability. *T. hamatum* produces trichoviridin 3-(3-isocyano-6-oxabicyclo (3, 10) hex-2-ch-5yl) acrylic acid and 3-(3-isocyano cyclopet-2-enzylidne) propionic acid. In addition, it produced three isonitriles among which isonitrin A has broad spectrum in activity. *T. longibrachiatum* produced trichodermin and trichobrachin. The cells exposed to antibiotics of *Trichoderma* spp., create ultra-structural changes like retraction of plasma lemma, breakdown of organelles, disintegration of cytoplasm, loss of turgor, weakening and death of host cells.

Cellulases

Trichoderma species are potential bio-control agents and producers of powerful cellulases (Papavizas 1985). Mandels et al. (1971) irradiated *T. viride* and produced a new strain that secreted twice as much cellulase as its wild parent. Improved strains of *T. reesei* were isolated through mutation and selection. It produced more cellulase than did the wild strains (Montenecourt and Eveleigh 1979). Baker (1991) found a perfect correlation between increased cellulase production and rhizosphere competence by mutants of *T. harzianum*. It is suggested that mutants use the mucigel on roots as a substrate. Mutants with rhizosphere competence were more efficient bio-control agents and induced increased growth responses from seed treatment than did the wild type parent. The quality and quantity of cellulases from *Trichoderma* spp. were improved by mutagenesis (Cuevas et al. 1994).

Lytic Enzymes

Proteases

Trichoderma species are well known producers of proteases. Proteolytic activity of *T. viride* was claimed to be involved in biocontrol of *Sclerotium rolfsii*. Serine proteases produced by *T. harzianum* played an important role in mycoparasitism of plant pathogens (Geremia et al. 1993). Autoclaved mycelium, fungal cell wall or chitin induces this enzyme and its production was repressed by glucose. Proteases are suggested to degrade cell wall, membranes and proteins released by the lysis of the pathogen, thus making the nutrients available for the mycoparasite (Goldman et al. 1994).

β-1,3 Glucanases

Lytic enzymes play a vital role in mycoparasitism and degrade the pathogen cell wall. The enzymes like chitinases, and β-1,3 glucanases lyse the host wall and this leads to the leakage of protoplasmic contents, which are in turn used as food material for the multiplication of antagonists (Cherif and Benhamou 1990; Elad et al. 1983; Tronsmo et al. 1993). Strains of *T. harzianum* produced a mixture of lytic enzymes comprising of chitinolytic and gluconolytic enzymes which are involved in mycoparasitism (Sivan and Chet 1989). Excretion of β-1,3 glucanase into growth medium and to the soil by *T. harzianum* was observed (Elad et al. 1982). The same was purified by Kitamoto et al. (1987). Carbon sources like laminarin, pustulan, cell walls of *R. solani* and mycelia of several fungi incorporated in the enzyme production medium induced the secretion of β-1,3 glucanase by *T. harzianum* (Jacobs et al. 1991). The purified endochitinase, chitobiosidase, N-acetyl-(β-glucosaminidase and glucan, 1,3-β-glucosidase and combinations inhibited spore germination and germ tube elongation of *Botrytis cinerea*. Combinations of the purified enzymes resulted in a synergistic increase in antifungal activity (Lorito et al. 1994a, b). High synergistic activity was observed by combining 1,3-β-glucosidases and chitinolytic enzymes (Tronsmo et al. 1993). This corresponds to the effect observed with combination of β-1,3 glucanase and endochitinase isolated from plants (Mauch et al. 1988). *T. harzianum* also produced N-acetylglucosaminidase, endochitinase, chitobiosidase and endo β-1,3 glucanases in the soybean rhizosphere with activity against *R. solani* (Dalsoglio et al. 1998).

Chitinases

Chitinase, the basic protein catalyses the hydrolysis of chitin. Chitin a linear polymer of β-1,4-N-acetyl glucosamine is often considered to be the second most abundant polysaccharide in nature (Deshpande 1986; Nicol 1991). The relationship between mycolytic enzymes, chitinases and β-1,3 glucanases produced by mycoparasitic fungi and their significance in fungal cell wall lysis and degradation have been well established (Elad et al. 1980, 1983). Assay of chitinase could be used as a basis for screening potential bio-control agents (Elad et al. 1982). *Trichoderma* spp. attack several plant pathogenic fungi by excreting lytic enzymes including β-1, 3 glucanase, proteinases and chitinases enabling them to degrade host cell walls and thus reduce disease incidence (Geremia et al. 1993; Chet et al. 1993; Lorito et al. 1993; Goldman et al. 1994). *T. harzianum* strain Tm had six distinct chitinolytic enzymes. Two were identified as β-1, 4-N-acetyl glucosaminidases. They hydrolyze chitin to N-acetyl glucosamine (Glc NAc) monomers. Four were endochitinases that randomly cleave at internal sites over the entire length of the chitin microfibril (CHIT 52, CHIT 42, CHIT 33 and CHIT31). *T. harzianum* – P1 released chimeric units from chitin termed as chitobiosidase (40 kDa) (Harman et al. 1993).

The involvement of *Trichoderma* chitinases in mycoparasitism was performed in liquid cultures supplemented with different carbon sources e.g. chitin, purified fungal cell walls, glucose or GlcNAc (Garcia et al. 1994; Limon et al. 1995). Complete degradation of mycelial walls of pathogenic fungi depends to a major extent on chitinolysis and hence the degrading ability to chitin by *Trichoderma* spp. assumes a greater significance in the antagonistic process than the other mechanisms/enzymes involved in the process (Cherif and Benhamou 1990). Chitinases and glucanases were produced by *Trichoderma* isolates, in soil, which had live mycelium of *S. rolfsii* and *R. solani*. High level of β-1,3 glucanase and chitinase activities were also detected by dual agar cultures of *T. harzianum* with *S. rolfsii* and *R. solani* (Elad et al. 1983). Direct interaction of *T. harzianum with R. solani*, strongly enhanced the endochitinase CHIT 42 (Carsolio et al. 1994). The spore germination and hyphal elongation of *B. cinerea*, *F. solani*, *F. graminearum*, *Ustilago avenae* and *Uncinula necator* were inhibited substantially by the combination of chitinolytic and gluconolytic enzymes purified from *T. harzianum* (Harman et al. 1993). The chitinolytic enzymes from *T. harzianum* were more active than that of the enzyme from other sources e.g. plant-bacteria and were effective against a wider range of fungi (Harman et al. 1993).

Sensing and Mycoparasitism by *Trichoderma*

In recent years biocontrol has been defined as a combination of different mechanisms working synergistically to achieve disease control (Howell 2003). *Trichoderma* species exhibit various modes of action including competition, antibiosis, mycoparasitism, ISR, and plant growth promotion. Synergistic action by *Trichoderma* spp., aided in exploring its potential for the management of plant pathogenic fungi such as *Rhizoctonia bataticola*, *Rhizoctonia solani*, *Botrytis cinerea*, *Sclerotium rolfsii*, *Sclerotinia sclerotiorum*, *Pythium* spp., *Phytophthora* spp., and *Fusarium* spp. Owing to the biocontrol ability of *Trichoderma*, it is being commercially used in United States, India, Israel, New Zealand, and Sweden (Howell 2003; Nakkeeran et al. 2005).

Mycoparasitism by *Trichoderma* involves nutrient competition (Chet 1987), the production of antifungal metabolites (Dennis and Webster 1971; Claydon et al. 1987; Schirmböck et al. 1994; Lorito et al. 1996), coiling around the fungal pathogen and formation of appressorium-like structures (Elad et al. 1983; Lu et al. 2004). Mycoparasitism relies on the production of lytic enzymes by the mycoparasite for the degradation of cell walls of the host fungus. Isolates of *Trichoderma* spp. coiled around the hyphae of *R. solani*, which consequently lost their cell contents and collapsed (Chu and Wu 1981). *Trichoderma* spp. attached to *S. rolfsii* or *R.solani* by hyphal coils, hooks, or appressoria. Lysed sites and penetration holes were found in hyphae of the pathogen following the removal of parasitic hyphae (Elad et al. 1983). *Trichoderma* coiled over *Pythium* resulting in cell wall lysis, vacuolation and coagulation of protoplasm (Lifshitz et al. 1986).

Hydrolytic enzymes including chitinases, glucanases, and proteases, are partially induced even before the direct contact with the host pathogenic fungi. Subsequently, it is followed by penetration of the cell wall of the host fungus and utilization of its cellular contents, which play a major role in biocontrol (Hjeljord and Tronsmo 1998).

The expression of the chitinase gene is induced in liquid culture by the cell wall of the host fungus, colloidal chitin, or the chitin monomer N-acetylglucosamine (Kubicek et al. 2001). The gene *nag1*, encoding N-acetylglucosaminidase in *T. atroviride* has a major impact on the induction by chitin of other chitinases (Brunner et al. 2003).

A diffusible factor released from *R. solani* was responsible for induction and transcription of the gene *ech42* encoding endochitinase 42 before physical contact during the mycoparasitic interactions between *Trichoderma* and *R. solani* (Cortes et al. 1998). During the physical contact, lectins in the pathogenic host's cell wall can induce coiling of the mycoparasite around the host hyphae (Barak and Chet 1986; Inbar and Chet 1994).

However, enzyme production even before the contact by *Trichoderma* on the host fungus and mycoparasitism are induced responses triggered by the molecules released by host fungi (Zeilinger et al. 1999). However, recent studies reveal that, regulation of genes associated with biocontrol activity involves highly conserved signalling compounds associated with the regulation of intracellular signal transduction pathway.

Heterotrimeric G-Protein Signaling and Mycoparasitism by *Trichoderma* G protein signaling comprises three parts such as a G protein-coupled receptor (GPCR), a heterotrimeric G protein (α, β, γ subunits), and an effector (Neer 1995). More than 1000 GPCR-encoding genes were cloned, described and characterized (Kolakowski 1994). Though the overall amino acid sequence similarities between GPCRs are low, the receptor proteins have a common seven transmembrane domains. The N-terminus is outside the cytoplasm and the C-terminus is inside the cytoplasm. Ligand binding to the receptor results in a conformational change leading to release of the G protein and exchange of GDP for GTP on the Gα subunit. Subsequently, GTP bound α dissociates from its ßγ partner. Later, the ßγ signaling subunits regulate the activities of downstream effector molecules (Gutkind 1998).

The reason behind the minimal amino acid similarities between GPCRs led to intensive research on the release of genome sequences. The availability of numerous fungal genomes and comparative genomics of GPCR pointed out that the receptors can be classified into nine groups (Lafon et al. 2006). The various classes include class I to class IX. Classes I and II comprise pheromone receptors with similarity to the yeast Ste2p and Ste3p receptors; classes III and V contain putative carbon source receptors and cAMP-sensors; class IV comprises *Schizosaccharomyces pombe* Stm1p-like nitrogen sensors; class VI, which is characteristic of filamentous fungi, comprises receptors with an RGS domain downstream of their transmembrane regions; classes VII and VIII have been identified only recently and share similarities with some vertebrate receptors; class IX comprises fungal opsins (Borkovich et al. 2004).

The heterotrimeric G–proteins are highly conserved. They act as signal transducers, which binds with cell surface receptors and connects the cytoplasmic effector proteins. These G-proteins are essential during secondary metabolism, sexual and pathogenic development. Besides, G-proteins are associated with pheromone signaling cascade and affect the virulence of fungi determined by developmental and morphogenetic processes (Bölker 1998).

G-protein α subunits consist of three major subgroups (Bölker 1998). The subgroup I is similar to the mammalian Gαi subunits associated with the inhibition of adenylate cyclase (Turner and Borkovich 1993). The subgroup II of fungal Gα proteins is devoid of the consensus site for pertussis toxin dependent ribosylation, involved with a biological function or a distinct phenotype. The subgroup III, is similar to the mammalian Gαs family that positively regulates the internal cAMP level (Bölker 1998).

Gene *tga1* of *T. atroviride* pertaining to the Gα subunit is associated with coiling and conidiation (Rocha-Ramirez et al. 2002; Reithner et al. 2005). The negative mutant of Δ*tga1* indicated that, G-protein α subunit affects vegetative growth, and extracellular secretion of antifungal metabolites, and chitinase production involved in *Trichoderma* biocontrol (Reithner et al. 2005). Besides the activities of chitinase, transcription of the *nag1* encoding (N-acetyl-glucosaminidase) and *ech42* encoding endochitinase 42 were declined in the mutant strain. The Δ*tga1* mutant was unable to overgrow and lyse *R. solani*, *B. cinerea*, and *S.sclerotiorum* (Reithner et al. 2005). Increased production of secondary metabolites 6-pentyl-α-pyrone and sesquiterpenes was noticed in *T. atroviride* with the *tga1* gene (Reithner et al. 2005).

T. atroviride Tga3 with the gene *tga3* pertaining to the subgroup III Gα subunit regulated the intracellular cAMP levels and was responsible for the virulence of the isolate. Besides, it also regulated, mycelia growth, conidial germination and conidiation (Zeilinger et al. 2005). Accumulation of chitinolytic enzymes inside the cell wall and retention in the cell wall is also regulated by the gene *tga3*.

Mitogen Activated Protein Kinase (MAPK) and Mycoparasitism by *Trichoderma* Mitogen activated protein kinase (MAPK) cascades transmit various signal molecules through sequential activation of serine/threonine protein kinases by phosphorylation. It regulates the gene expression in different biological processes such as sporulation, mating, hyphal growth and pathogenicity (Xu 2000). MAPKs in *Trichoderma* belong to the family of yeast, which have 5 MAPK genes and fungal extracellular-related kinases (YERK1), a class also comprising MAPKs such as Pmk1 from *Magnaporthe grisea*, Fmk1 from *Fusarium oxysporum*, Bmp1 from *B. cinerea*, or Ubc3/Kpp2 from *Ustilago maydis*. One school of thought also explains the contradictory role of MAP kinase in the production of mycoparasitism-related enzymes by *T. virens*, (Mukherjee et al. 2003).

The MAPK gene of *T. virens* isolateTvk1 regulates conidiation, hydrophobicity and the expression of genes coding for cell wall proteins during development stages of *T. virens* (Mendoza-Mendoza et al. 2007). MAPK gene from *T. atroviride* (Tmk1) showed 98 % identity with *T. virens* TmkA/Tvk1 (Reithner et al. 2007). Besides hyperparasitism, MAPK signaling in *T. virens* also induced systemic resistance during the interaction of *Trichoderma* with the plant. Conidia of *Trichoderma* germinated in proximity to cucumber roots. Δ*tmkA* mutants of *T. virens* were also able to colonize the plant roots as effectively as the wild type strain. However, they failed to induce full systemic resistance against the *Pseudomonas syringae* pv. *lacrymans*. It suggested that *T. virens* needs MAPK signaling to induce full systemic resistance (Viterbo et al. 2005). *T. harzianum* ThHog1 is also involved in neutralizing the reactive oxygen species, produced by the parasitized fungi during mycoparasitism (Delgado-Jarana et al. 2006).

cAMP Signaling and Mycoparasitism by *Trichoderma* In general, cAMP the intracellular messenger involved in signaling in fungi is associated with the control of differentiation, sexual development, virulence, monitoring of the nutritional status, and stress. Besides, transcription and cell cycle progression are also influenced through cAMP pathway (Kronstad et al. 1998). The membrane-associated adenylate cyclase regulate the synthesis and cAMP levels. In addition, it also regulates a cAMP-specific phosphodiesterase involved in degradation.

The subunits of heterotrimeric G-proteins regulate the activity of adenylate cyclase, which synthesizes the intracellular messenger cAMP. Stimulation of cAMP-depend on Protein kinases (PKA). Protein kinases (PKA) comprise two regulatory and two catabolic units associated with growth, morphogenesis, and virulence processes of fungi (Dürrenberger et al. 1998). It determines the functions of cAMP (Dickman and Yarden 1999).

Induction of endoglucanase in *T. reesei* is enhanced by cAMP. It served as a positive effector responsible to antagonize and overgrow *Pythium ultimum* and provided protection of zucchini plants against *P. ultimum* blight (Seidl et al. 2006a). Likewise, exogenous application of cAMP increased coiling of *T. harzianum* (Omero et al. 1999) and triggered the substances that increase the intracellular levels of cAMP (e.g. dinitrophenol, caffeine, aluminum tetra fluoride) (Silva et al. 2004). cAMP signaling is essential for the induction of conidiation in *T. viride* and *T. atroviride*. Cloning the gene (*pkr-1*) encoding the regulatory subunit of protein kinase A (PKA) from *T. atroviride* confirmed that, it was responsible for the light response associated with growth and conidiation, that acts as a prerequisite for mycoparasitism (Casas-Flores et al. 2006). Photo induction of conidiation in *T. viride*, is accompanied by a rapid increase in the intracellular level of cAMP (Gresik et al. 1988), and exogenous cAMP induced conidial formation in colonies exposed to illuminated and dark conditions (Nemcovic and Farkas 1998). The gene *tac1* of *T. virens* encodes for adenylate cyclase, which regulates cAMP signaling. Deletion of the *tac1*gene in *T. virens* lowered the intracellular cAMP signaling even below the detectable limits. It reduced the growth rate, prevented sporulation in darkness and was unable to hyperparasitize *S. rolfsii*, *R. solani*, and *Pythium* sp. (Mukherjee et al. 2007). Further, it reduced secondary metabolite production and thus lost the mycoparasitic nature on fungal pathogens. Genes associated with mycoparasitism are listed in Table 4.2.

Volatile and Nonvolatile Secondary Metabolite Based Antibiotic Compounds

Mycoparasitic *Trichoderma* produce cell wall-degrading enzymes (CWDEs) and antibiotics as secondary metabolites of both volatile and non volatile nature. Volatile antibiotics up to C4 chain length consist of ethylene, hydrogen cyanide, alcohols,

Table 4.2 Genes associated with mycoparasitism

Gene	Function	Primer sequence	References
Acid sphingomielinase (*asm*)	hydrolases that cleave sphingolipids, a common component of plasma membranes,	Forward: GCGAAGCATCTCGGCTATTGTAGT	Dickson (1998)
		Reverse: TCAAGTTGTGAACCGCTACTCGTC	
β-1,3-endoglucanase (*bgn*)	Cell wall degrading enzymes	Forward: TCAACATCGCCAACGTCAACGAC	Lorito et al.(1998) and Steindorff et al. (2012)
		Reverse: TGCCAATACGGGAACCAGTGATC	
Chitinase 33 (*chit*)		Forward: TGGAGCTCAACAGGCGCTGC	
		Reverse: ACGACGGCACTGCCAAAGGG	
Endochitinase 42 (*endo*)		Forward: AAGGGTTACTACAGCTACAACGCC	
		Reverse: ACTTGAGGTAGGCAACCTTGGTGT	
glycosyl hydrolase (*glyc*)	Hydrolases - hydrolyse the glycosidic bond between two or more carbohydrates, or between a carbohydrate and a non-carbohydrate moiety	Forward: GAAATGTTGTCGTCACCAGACGGT	Henrissat and Bairoch (1996)
		Reverse: GGCCGCGATTGCTGTTTCATAGT	
Exo-rhamnogalacturonase (*exo*)	Hydrolases – belong to the group of pectin-degrading enzymes	Forward: TTACCTGAAGACATGGGCGGGAAT	Suykerbuyk et al. (1995)
		Reverse: GCCTTCCGCCAATCAGCTTAACAT	
Amine oxidase (*aoc*)	Genes related to amino acids	Forward: ATACACCCGAAGGAACCTTGTTGG	Yagodina et al. (2002)
	Metabolism – role in early stage of interaction	Reverse: TAGCGTGCCTCAATCTCCTTAGCA	
Phospholipase d (*pld*)	Transduction cascades, protein modification and fungal morphogenesis	Forward: TGGGAAGACGTTGCACACACAAAC	Dickman and Yarden (1999)
		Reverse: AAATTGTCGTAGTCGTCCCAGGTG	
Checkpoint-like Protein (*chk1*)		Forward: TGCTGCCTTCCTTGGATGTAGTAG	
		Reverse: AAACATGGTGGCAACGGGTAACG	
Serine threonine-protein kinase (*sck1*)		Forward: ATGCTGAAGAGCTTAAACGCCACC	
		Reverse: ACTTTGGCTTGAAGGGTGGAGAG	

(continued)

Table 4.2 (continued)

Gene	Function	Primer sequence	References
Senescence-associated protein (*sag*)	Senescence-associated protein	Forward: AGCTCACGTTCCCTATTAGTGGGT	Maheshwari and Navaraj (2008)
		Reverse: ATCCTTCGATGTCGGCTCTTCCTA	
mbl2-like secreted (*mbl2*)	Involved in recognition, attachment, adhesion and appressorium development	Forward: TTGCTACGAGGGAGTTTGTTCCTG	Kulkarni et al. (2003)
		Reverse: TGGAGTTGCACTGGTCTGAAGT	
Serine protease (*ser*)	Genes related to amino acids	Forward: TGGAAGGGAGTGACCAAGCCTG	Sharma et al. (2011) and Liu et al. (2009)
	Metabolism - role in early stage of interaction	Reverse: GGAAAGGTCAGGAGTGCTATCGGG	
Aquaporin (*aqp*)	Osmoregulation of cells	Forward: GTTGATGGCATAACCAGTCTCCCA	Pettersson et al. (2005)
		Reverse: CAACAACATTGGAGCCGGAAACCT	
Domain membrane protein (*duf*)	Involved in recognition, attachment, adhesion and appressorium development	Forward: TCCAATCCTTGCCGACGTAGTTGA	Kulkarni et al. (2003)
		Reverse: TGCCAAGATCACATGGGTCGTTCT	
Peptide transporter (*ptr2*)	Genes related with amino acids	Forward: AGTCATCTGGTTGTAGGCCAGGAA	Vizcaíno et al. (2006)
	Metabolism – role in early stage of interaction and mycoparasitic process	Reverse: AAATTGTCGTAGTCGTCCCAGGTG	
QID74 protein (*qid*)	Cell wall protection and recognition, attachment and formation of specialized structures such as appressoria	Forward: CAGAAGAAGTGCGTGTGCAACAAG	Rosado et al. (2007)
		Reverse: AGCTAGCATCTTTGCCGCAGTTTG	
Eight cysteine-containing domains (*cfem*)	Involved in recognition, attachment, adhesion and appressorium development	Forward: GCGTCCGCAAAGAAACAACCTTCT	Kulkarni et al. (2003)
		Reverse: AGAGAGCGGTGTTTGTAGCGATGA	

aldehydes and ketones. The non volatile antibiotic compounds include peptide antibiotics like peptaibols (Keszler et al. 2000). Peptaibols have antibacterial and antifungal activity (Rebuffat et al. 1999; Chugh and Wallace 2001; Jen et al. 1987; Schirmbock et al. 1994). The spectrum of antifungal activity increases along with cell wall degrading enzymes (Lorito et al. 1996). Antimicrobial peptaibols, are linear peptides with 5–20 residues. Residues have three structural characteristics i.e. α- α′ dialkylated amino acids with an abundance of α -isobutyric acid (Aib) under high proportion; an acetyl based N-acyl terminus and a C-terminal amino alcohol such as phenyl-alaninol or leucinol.

Short Peptide Siderophores

Trichoderma species compete for nutrients and create stress to the soil borne pathogens. During iron limited conditions, fungi excrete siderophores to solubilize the iron either from rhizosphere or non-rhizosphere soil. In general, fungal siderophores are short peptides consisting of non-proteinogenic amino acids (Leong and Winkelmann 1998). Several species of *Trichoderma* produce iron-chelating siderophores (Chet and Inbar 1994) but they have not been characterized. Besides, a monohydroxamate (cis- and trans-fusarinines), a dipeptide of trans-fusarinine (dimerum acid), and a trimer disdepsipeptide (copragen) based siderophore have been described in *T. virens* (Jalal et al. 1986).

Biosynthesis of Antibiotics and Siderophores

Peptaibols with an unusual amino acid content and siderophores are produced non-ribosomally by large multifunctional peptide synthetases (NRPSs). Multifunctional enzymes associated with the synthesis of peptaibols and siderophores bring together compounds from a wide range of precursors including non-proteinogenic amino acids and hydroxy or carboxyl acids (Marahiel et al. 1997). NRPS collectively organize into repetitive synthase units that complete the elongation step of different amino acids. These in turn coordinate various domains such as adenylation, thiolation and condensation associated with the peptide synthesis (Kleinkauf and von Dohren 1996). The functions of each domain include ATP dependent activation to form a peptide bond, transfer of the acyl adenylates to specific thiols located in the enzyme-bound cofactors (40-phosphopantetheine) and condensation of the amino acids to form a peptide bond. The synthesized peptaibols are brought into functional form through the incorporation of the monomers by epimerization or N-methylation or by the peptide backbones such as acylation, glycosilation or heterocyclization. Synthesis of these peptides is catalyzed either by specialized domains or by fusion to polyketide synthase (PKS) modules (von Dohren et al. 1997; Cane et al. 1998). Different domains are associated with the synthesis of peptide maps in 1:1 manner to the amino acid in the presence of non-ribosomal multifunctional peptide synthetases. The largest NRPS gene –tex1 comprising of 18-module peptaibol synthetase has been detected in *T. virens* (Wiest et al. 2002).

Differential Expression of Genes Associated with Mycoparasitism

Antagonistic abilities of *Trichoderma* spp. involve the production of antifungal metabolites and cell wall-degrading enzymes (CWDE). Some of the genes involved in biocontrol of plant pathogens have been used to promote plant resistance to pathogens and salt stress (Lorito et al. 1998). Furthermore some of the biologically important proteins from *Trichoderma* have been successfully produced for agricultural and industrial applications (Lorito et al. 2010).

The mycoparasitic relationship of *T. harzianum* with *Fusarium solani* upregulated the expression of genes. Besides, *Trichoderma* species could sense the presence of its host and could trigger the expression of specific genes even before contact (De la Cruz et al. 1995). After confrontation by *T. harzianum* with the cell wall of *F. solani* the genes β-1,3-endoglucanase (bgn), chitinase 33 (chit), endochitinase 42 (endo), exo-rhamnogalacturonase (exo), glycosyl hydrolase (glyc), amine oxidase (aoc), phospholipase d (pld), checkpoint-like protein (chk1), serine threonine-protein kinase (sck1), senescence-associated protein (sag), aquaporin (aqp), duf895 domain membrane protein (duf), peptide transporter (ptr2), QID74 protein (qid) and eight cysteine-containing domain (cfem) were upregulated (Pabline et al. 2013). Exo-rhamnogalacturonases belong to the group of pectin-degrading enzymes (PDE) and could be involved in cell wall degradation of *F. solani*. For instance, an endopolygalacturonase (EPG) produced by *T. harzianum* is known to be involved in the cell wall degradation of *Rhizoctonia solani* and *Pythium*.

The intense cell wall degradation of *F. solani* was due to the over expression of three genes encoding CWDE, β-1,3-endoglucanase (bgn), chitinase 33 (chit) and endochitinase 42 (endo) after contact (Steindorff et al. 2012). The expression of these genes was induced by the cell wall of *F. solani*. Besides, the glucose availability strongly represses these genes. Furthermore, the pathogens *R. solani*, *F. oxysporum* and *S. sclerotiorum* were hyperparasitized by *T. harzianum* due to the upregulation of β-1,3-endoglucanase (bgn), chitinase 33 (chit) and endochitinase 42 (endo) (Sharma et al. 2011).

Trichoderma Triggers Induced Systemic Resistance (ISR) and Systemic Acquired Resistance (SAR)

Colonization of fungal biocontrol agents on the rhizosphere triggers ISR and SAR mediated through salicylic acid (SA) and jasmonate/ethylene (JA/ET). Rhizosphere colonization by *Trichoderma* alters the host physiology by inducing rapid ion fluxes and an oxidative burst, coupled with the deposition of callose and synthesis of polyphenols (Shoresh et al. 2010). It is succeeded by the involvement of SA and JA/ET signals in coordination with NPR genes, which in turn determines the varying degree of resistance to the invading pathogens (Shoresh et al. 2010).

One school of thought explained that ISR triggered by *Trichoderma* spp., via JA/ET mimics the ISR triggered by plant growth-promoting rhizobacteria (PGPR). But, one another school of thought explained that, interaction of the host plant with the increased population dynamics of *Trichoderma* can induce SAR similar to the resistance evoked by necrotrophic pathogens (Segarra et al. 2007; Salas-Marina et al. 2011; Yoshioka et al. 2012). Molecular cross talk between mitogen-activated protein kinase (MAPK) from cucumber and a MAPK from *T. virens* triggers the downstream defense responses in cucumber (Viterbo et al. 2005; Shoresh et al. 2006).

Increased content of alpha amino isobutyric acid in xylanase, peptaibols, alamethicin and trichovirin II produced by *Trichoderma* spp. induces an immune response in plants (Druzhinina et al. 2011; Luo et al. 2010). *Trichoderma* gene Sm1/Epl1 secretes a cysteine-rich hydrophobin-like protein in abundance belonging to the cerato-platanin (CP) family, and triggers ISR in maize (Mukherjee et al. 2012; Djonovic et al. 2006, 2007; Seidl et al. 2006b). Further, the glycosylated state of Sm1 in the monomeric form alone triggers ISR. But the non glycosylated monomeric form of Sm1 is susceptible to oxidative-driven dimerization and thereby cannot function as an elicitor to trigger ISR. Sm1 coding for the cerato-platanin with carbohydrate (an oligomer of N-acetyl glucosamine) binding properties is highly conserved and might be responsible for elicitation of ISR (de Oliveira et al. 2011). Besides, defense responses in maize were also triggered by a PKS/NRPS hybrid enzyme (Mukherjee et al. 2012).

Indirect Mechanism of Action

Induced Resistance

Induced resistance is a plant response which occurs following the challenge inoculation of an antagonist that triggers the expression of a set of genes which encode for pathogenesis – related proteins such as chitinases, β-1, 3-glucanases and thaumatin – like proteins with antifungal activity (Linthorst 1991). Synthesis of phytoalexins may also occur (van Peer and Schippers 1992).

Plant Growth Promotion

Growth promotion may occur either directly or indirectly. Promotion of growth may occur either through bio-control of deleterious pathogens (Baker 1989) or through the production of plant hormones e.g. auxin, cytokinin or gibberellins (Arshad and

Frankenberger 1991). Baker et al. (1984) found that *T. harzianum* can also stimulate plant growth, including floricultural and horticultural plants (Chang et al. 1986). Pepper seed germinated two days earlier in raw soils containing the fungus than in untreated controls. Flowering of periwinkle was accelerated, the number of blooms per plant on chrysanthemum was increased, and the height and weight of other plants were greater in either steamed or raw soil infested with *T. harzianum*. These responses have occurred consistently with population densities of *T. harzianum* higher than 10^8 cfu g^{-1} of soil, whether the bio-control agent was applied as conidial suspension or as mycelium and spore in a peat bran medium.

Growth stimulation by *T. harzianum* could be the result of production of plant hormones by an antagonist, increased uptake of nutrients by the plant, through nutrient mobilization, or the control of one or more subclinical pathogens. *Pythium* spp. are capable of stunting plants and hinder the nutrient uptake of roots (Becker and Cook 1988). Hence suppression of *Pythium* spp. could increase the plant growth (Salt 1978). Increased growth by *Trichoderma* spp. was also induced by a diffusible growth-regulating factor produced by these organisms (Windham et al. 1986).

Mass Production and Formulations

It is not sufficient to treat plants or soil with viable propagules; the propagules also have to be properly formulated. What can transform a potential biological control agent from a laboratory curiosity to a commercially successful product?" It is the formulation (Connick et al. 1990). A successful bio-control formulation is one, which is economical to produce, safe, stable in the environment and easily delivered and should enable the bio-control agent to act effectively and consistently under varied environmental conditions. The major factor in the formulation is the nutrient status of the substrate or additives, since the establishment of the antagonist in soil is one of the main difficulties to overcome in the application of antagonistic microorganisms. Introduction of antagonists through organic carriers alleviate the competition from autochthonous microorganisms, since the organic carriers serve as both protection and a food base during the establishment phase of the antagonist (Deacon 1988; Steinmetz and Schonbeck 1992). Delivering of *Trichoderma* spp. to the site of infection via the organic food bases like diatomaceous earth granules with molasses (Backman and Rodriguez-Kabana 1975), wheat bran (Henis et al. 1978), wheat bran + saw dust (Elad et al. 1980), wheat bran + peat (Sivan et al. 1984), molasses yeast (Papavizas et al. 1984), alginate pellets (Fravel et al. 1985), pyrax (Papavizas and Lewis 1989), vermiculite + wheat bran (Lewis et al. 1991; Nakkeeran et al. 1997) and processed manure pellets (Kok et al. 1996) allow establishment and multiplication of the antagonist in the soil, resulting in high population levels during an extended period of time.

Talc Based Formulation

The Tamil Nadu Agricultural University, Coimbatore, has developed the technology of mass production of talc-based formulation of *Trichoderma viride*, and *Pseudomonas fluorescens* for seed treatment. Annually, it produces this formulation to cover 20,000 ha. Several private industries in Coimbatore, Bangalore, Chethali, Delhi and Chennai produce the same in large quantities. However, the demand exceeds the present supply. The annual requirement of *Trichoderma* has been estimated as 5000 tons to cover 50 % of the area in India. Indirectly it also creates self-employment opportunities to the unemployed youths. The first commercial seed treatment formulation of a bio-control agent in India was developed by Jeyarajan et al. (1994). *T. viride* was grown in molasses yeast medium for 10 days in flasks. Then 2.5 l of the culture were inoculated to 50 l of sterilized molasses yeast medium in a fermenter. It was incubated for 10 days with 4–8 h aeration/day. The fungal biomass and the broth were mixed with 100-kg talc (super white) powder and 500 g of carboxy methylcellulose as a sticker. It was dried in shade for 72 h and packed in alkathene bags. The initial population of *Trichoderma* in the product was 300×10^6 cfu/g. The product should contain a minimum of 20×10^6 cfu/g at the time of use. This is applied at the rate of 4 g per kg of seed. The shelf life was 4 months. Angappan (1992) found that in chickpea treated with this product the rhizosphere population was maintained at $11–13 \times 10^3$ cfu per gram throughout the crop growth stage. Ranganathan et al. (1995) found that gypsum was a good substitute for talc but was much cheaper than talc.

Industrial Wastes

Nakkeeran and Jeyarajan (1996) tested two industrial wastes, namely precipitated silica and calcium silicate, in the place of talc and found them to give a population of $99,104 \times 10^6$ cfu/g respectively, compared to 143×10^6 cfu/g in talc substrate after 4 months of storage. These two substrates were also much cheaper than talc.

Diatomaceous Earth Granules

Diatomaceous earth granules were added into a broth consisting of 100-ml blackstrap molasses, 900 ml of water, 3 g each of $KNO_3$and KH_2PO_4 till the level of saturation. It was autoclaved at 121° C for 15 min and spread in shallow pans to a height of 3–5 cm and autoclaved again. *T. harzianum* (3 day old culture) was homogenized in a blender for 3 s and mixed with sterilized granules in shallow pans and incubated at 25C for 4–7 days. Clumps were broken up and granules air dried with frequent stirring and used as an inoculum. The inoculum was mixed at 1.1 (v/v) with sterilized diatomaceous earth granules impregnated with 10 % molasses solution. It was applied to peanut at 140 kg/ha on 70 and 100 days after sowing to control *Sclerotium rolfsii*. The disease was reduced by 42 % over the control and yield increased by 13.5 % (Backman and Rodriguez-Kabana 1975).

Wheat Bran: Saw Dust Formulation

Wheat bran: Sawdust: tap water mixture (3:1:4 v/v) is taken in polypropylene bags and autoclaved for 1 h at 121 °C for two successive days. The bags were inoculated with *Trichoderma harzianum* and incubated in illuminated chambers for 14 days at 30 °C. It was applied at the time of sowing and mixed with the soil to a depth of 7–10 cm with a rotary hoe. It increased yield of beans (1500 kg/ha), tomato (300 kg/ha), cotton (500 kg/ha) and potato (40–600 kg/ha) and controlled *Sclerotium rolfsii* and *Rhizoctonia solani* (Elad et al. 1986).

Wheat Bran: Peat

Wheat bran: Peat mixture (1:1 v/v) was autoclaved for 1 h. Substrate moisture was adjusted to 50 % (W/W) with sterile water, medium was inoculated with 0.1 ml of a conidial suspension containing 2×10^4 conidia/ml and incubated for 7 days at 30 °C. It was mixed with rooting mixture for tomato at 10 % v/v to control crown rot (*Fusarium oxysporum f.* sp. *radicis-lycopersici*). The disease was reduced by 29.7 % over the control and yield increased by 7 % (Sivan et al. 1984).

Vermiculite: Wheat Bran

Trichoderma was multiplied in molasses – yeast medium for 10 days. Vermiculite (Grade 4) and milled wheat bran (250 mesh) were heated in a hot air oven at 70 °C for 3 days using metal pans. Vermiculite (100 g), wheat bran (3.3 g), liquid culture (14 ml) and 0.05 N HCI (17.5 ml) were mixed and packed. This was immediately used for soil application (Lewis et al. 1991). Vidhya (1995) applied this formulation at 250 kg/ha to mung bean and the application resulted in a 41 % reduction in root rot (*M. phaseolina*) and a 91 % increase in yield.

Alginate Pellets

Sodium alginate (20 g) was dissolved in 750 ml water at 40 °C on a stirring hot plate. Wheat bran ground to pass through a 0.425 mm mesh screen was placed in a glass blender container with distilled water (50 g/250 ml). Kaolin can also be used in place of bran. It was autoclaved for 30 min and cooled. Fermenter biomass (16–21 g/l) was added to provide 7×10^6 conidia and chlamydospores. The mixture containing fungus, alginate and bran or kaolin was added dropwise into a 500-ml gellant solution (0.25 M $CaCl_3$, pH 5.4). As it entered, each droplet gelled and a distinct spherical bead formed. After 20 min in the gellant, beads were separated from the solution by gentle filtration, washed and dried for 24 h in a stream of air at 25 °C (Lewis and Papavizas 1986).

Other Substrates

The following substrates were also found to support the growth of *Trichoderma viride* and *T. harzianum* (Kousalya and Jeyarajan 1988): farm yard manure, gobar gas slurry, press mud, paddy chaff, rice bran and groundnut shell.

Shelf Life

Shelf life of a bio-control agent plays a crucial role in the storage of a formulation. In general the antagonists multiplied in an organic food base have a longer shelf life than the inert or inorganic food bases. Viability of the encapsulated alginate pellets of *T. harzianum* isolate (Thr IDI) remained high for at least six months when stored at 5 °C and was reduced significantly when stored at 2 °C (Dandurand and Knudsen 1993). Jeyarajan et al. (1994) developed talc, peat, lignite and kaolin based formulations of *T. viride*, which had a shelf life of four months. Shelf life of the same in gypsum-based formulation was also four months, and was cheaper than talc based formulations (Ranganathan et al. 1995). Vermiculite bran acid fermenter biomass (VBA-FB) of *T. viride* recorded the highest mean population of 20.5×10^7 cfu/g up to 75 days of storage at room temperature (Nakkeeran et al. 1997).

Methods of Application

Biocontrol agents can be applied to various plant parts e.g. seed, root, foliage, inflorescence and also the soil. For this purpose several methods were developed which enhanced the yield considerably (Nakkeeran et al. 1995; Nakkeeran and Renukadevi 1997).

Seed Treatment

Seed treatment is an alternative method for introducing bio-control agents into the soil plant environment. The efficacy of seed treatment depends on the ability of the antagonist to multiply in the rhizosphere region. Seed treatment with *T.harzianum* reduced the disease caused by *R. solani* on cotton in field conditions (Elad et al. 1982). Treatment of black gram, green gram, pigeon-pea, cowpea, groundnut, sunflower, sesamum and cotton with *T.viride* at the rate of 4 g/Kg reduced the incidence of root rot and wilt (Dinakaran et al. 1995; Jeyarajan et al. 1994; Jeyarajan and Nakkeeran 1996; Muthamilan and Jeyarajan 1996; Nakkeeran and Renukadevi 1997).

Solid Matrix Priming

It is a process in which moistened seeds are mixed with an organic carrier and the moisture content of the mixture is brought to a level just below that required for seed sprouting. Solid matrix priming can further enhance the efficacy of antagonist in treated seeds. *Trichoderma* which grows on the seed surface during the priming process increases in numbers and other microbes may not easily dislodge it. A slurry of *Trichoderma* is first added to seeds followed by addition of lignite and water. The primed seeds were incubated for 4 days at 80–100% RH. During this period *Trichoderma* colonized the seed and sporulation was evident. In *Pythium ultimum* infested soil the stand was increased to 70–80% as against 10% in the control. In tomato seed the *Trichoderma* population increased tenfold due to solid matrix priming (Harman et al. 1989).

Soil Application

For effective management of soil borne diseases, a high population of the antagonist in the soil is necessary. Adams (1990) defined efficiency of biocontrol agents as the ratio of number of propagules of mycoparasites required to obtain disease control to the typical inoculum density of a plant pathogen. Therefore attempts were made to develop a suitable delivery system to soil. For controlling *R. solani*, a *Trichoderma* population of 5×10^6 was required for each propagule of *R. solani*. Addition of wheat bran based inoculum to soil gave an 80% reduction of root rot over the control in chickpea and bean (Elad et al. 1986). Incidence of urdbean root rot was reduced by 91.3% by adding *T.viride* + *T. harzianum* to soil (Kousalya and Jeyarajan 1988). Delivering *T. harzianum* through soil during sowing increased the percentage survival of peanut (90%), while in control none of the plants survived (Muthamilan and Jeyarajan 1996).

Cut Surface Application

Ricard (1981) developed a special shears to apply *T. viride* simultaneously with pruning to protect fruit trees against silver leaf disease caused by *Chondrostereum purpureum*. The shears have a reservoir for suspension of *T. viride*. Each pruning cut was covered by a spore suspension.

Hive Insert

Thomson et al. (1992) developed an innovative method of application of a bio-control agent right in the infection court at the exact time of susceptibility. *Botrytis cinerea* (fruit rot of strawberry) was effectively controlled by *T. virens* through honey bees which acted as vector. Peng et al. (1992) developed a novel and more efficient method of applying inoculum of *T. virens* on talc and corn meal (5×10^8 cfug/g), which was placed inside the beehive in a dispenser. Bees acquired the conidia on their legs and bodies as they crawled. Each bee had a spore load of $88–1800 \times 10^3$. Each flower received 1.6 to 27×10^3 conidia of the antagonist. It suppressed *B. cinerea* on stamens (54 %) and petals (47 %) and controlled fruit rot.

Factors Influencing Bio Efficacy

Abiotic factors influence the efficacy of bio-control agents in soil. The factors include pH, moisture, temperature, soil type, components of soil atmosphere, inorganic and organic constituents of soil and the quantity and type of pesticides applied to soil.

pH

Hydrogen ion concentration played a major role in the adaptability of bio-control agents to their nutrient environment. The activities of *Trichoderma spp*. were more pronounced at low pH levels and the efficacy was influenced by acidic conditions (Chet and Baker 1980, 1981). The activity of *T. lignorum* was poor in neutral and alkaline soils (Dhingra and Khare 1973). Acidic pH favored disease suppression induced by *T. harzianum* (Chet and Baker 1980; Liu and Baker 1980; Marshall 1982; Harman and Taylor 1988) and *T. hamatum* (Chet and Baker 1981). The spore germination (Chet and Baker 1980), mycelial growth, conidiophore production (Chet and Baker 1980), antibiotics production (Dennis and Webster (1971) and the activity of lytic enzymes (Chet and Baker 1980) were enhanced under acidic conditions. Jeyarajan et al. (1994) found that the isolates of *T.viride* perfomed in a wide range of pH varying from 5.0 to 9.0. Since the isolates of *T.viride* perform in a wide range of soil pH, a composite, compatible formulation of *T. viride* could be developed and used in disease management programs.

Moisture

The soil moisture content is more important than soil reactions in producing changes in microbial flora in soil. It affects the growth of the antagonist. The bacterial population dropped rapidly as the soil moisture fell below 15–20 %, but it was not found to affect fungi and actinomycete populations (Krishnamoorthy 1987). The minimum relative humidity required for the growth of *Trichoderma* was 91 %. Growth of *T.viride* was higher at 40–60 % moisture than at higher soil moisture levels. Jeyarajan et al. (1994) observed that all the isolates of *T.viride* and *T.harzianum* survived uniformly well at 40 % followed by 60 % moisture holding capacity.

Competitive Saprophytic Ability (CSA)

For effective biological control of soil-borne plant pathogens, a major consideration is antagonist proliferation after introduction into the soil or rhizosphere, by producing inoculum in excess to survive, grow and proliferate. A high level of competitive saprophytic ability is a prerequisite for surviving in soil and the rhizosphere (Baker and Cook 1988).

CSA is the summation of physiological characteristics that make for success in competitive colonization of dead organic substrates. Ahmad and Baker (1987a, b) reported a direct correlation between cellulose production, biomass from growth on cellulose or CSA on cellulose substrate in soil with a high degree of rhizosphere competence among strains of *Trichoderma* spp. The CSA index was directly correlated with cellulose production. Mutants with higher cellulose activity could efficiently utilize cellulose substrates on or near the root and thus are considered rhizosphere competent. A good correlation between the saprophytic activity of various strains of *Trichoderma* and their activity against sclerotium forming soil fungi was reported (Davet 1987).

Population Dynamics of *Trichoderma*

Soil

The soil ecosystem is a hostile environment; introduced microorganisms often cannot establish and eventually disappear. The bio-control efficacy of *Trichoderma* isolates seems to depend on the population size, reached after introduction into soil. For effective bio-control of soil-borne pathogens, a major consideration is antagonist proliferation after introduction into the soil or rhizosphere. A successful antagonist, to survive better in the soil and rhizosphere, should have the ability to proliferate well in the introduced environment (Baker and Cook 1974). Population densities of *T. viride* (T-1-R4) and *T. harzianum* (WT-6-24) increased about 10^4 and 10^3-fold respectively in natural soil during the first 3 weeks of incubation (Lewis and Papavizas 1984). The decline in the population of *T. viride* in the soil might be due to lysis and disintegration of conidia. The stable population densities of *T. viride* from 9 to 36 weeks of incubation may be due to the survival of chlamydospores. In no case did conidia of *Trichoderma* and *Gliocladium* proliferate in soil without the addition of a food base (Papavizas 1985). Pyrax (Clay powder), alginate pellets, and vermiculite-bran mixture-based formulations allowed establishment and multiplication of the antagonist in soil, resulting in high population levels during an extended period of time. The activity and proliferation of *Trichoderma* spp. in the protection of radish seeds against *Rhizoctonia solani* was effective only in acidic soils (Chet and Baker 1980, 1981). A food base such as ground wheat bran enables the fungal propagule in a given preparation to germinate and to colonize the soil. In sterile conditions the propagation of *T. harzianum* was much greater than under non-sterile soils. The incorporation of *T. harzianum* conidia through processed manure pellets was essential for the successful colonization in non-sterile soils. The population level in the acidic sand was higher than in the alkaline sand (Kok et al. 1996).

Seeds

Bio-control agents must proliferate rapidly and become established at the place where they are applied. The first 12–24 h after planting is a crucial period for the bio-protectant applied as a seed treatment against soil-borne pathogens and they must grow and establish on the seed coat (Hubbard et al. 1983; Taylor and Harman 1990). Solid matrix priming is the process, in which seeds are moistened and mixed with a finely ground organic carrier, sufficient water added to achieve the appropriate moisture potential for priming and then incubated for a given duration at a constant temperature. Organic carriers have been shown to enhance the efficacy of *Trichoderma* spp. The bio-agent proliferates during the incubation period and becomes established, and colonizes the seed surface (spermosphere) thoroughly before planting (Harman et al. 1981). Primed seeds consistently emerge more rapidly than the untreated seeds and provide better stands under adverse environmental conditions than do untreated seeds (Harman and Taylor 1988). Solid matrix priming of tomato seeds increased the number of *Trichoderma* propagules by one order of magnitude in the spermosphere. The effectiveness of bio-control agents may depend partially on their ability to proliferate during a short period of favorable environmental conditions before they encounter plant pathogens. The number of colony forming units (cfu) of *Trichoderma* increased on seeds during the matrix priming in Agro-lig by about tenfold. Number of *Trichoderma* on matrix priming were 10^4 cfu per seed after 4 days of incubation, while on seeds treated with *Trichoderma* alone they were about 10^3 cfu per seed. Hence the increase in the cfu of *Trichoderma* provided better emergence of tomato (Harman and Taylor 1988).

Commercialization

Industrialization of biocontrol agents requires linkages between corporate and academic bodies. The success and commercialization of a scientific innovation depends on the availability and usefulness of the technology to the end users. It depends on the linkages between scientific organizations and industries. Biocontrol technology becomes a successful component of plant protection only when it is commercialized. The stages of commercialization are shown in Fig. 4.1.

Stages of Commercialization

Isolation of Antagonist

Isolation of an effective antagonist plays a prime role in disease management. Antagonists are usually isolated from disease suppressive soil or from the rhizosphere of a healthy plant. They can be also isolated by baiting the soil with resting structures of pathogens, to which they are attracted. Isolation source determines the ability of an antagonist to perform well against a virulent pathogen. Antagonists are isolated by pour plate or spread plate technique, followed by serial dilution. Certain special media can be utilized in isolating antagonists viz., *Trichoderma* selective medium. Besides, the compatible isolates of *Trichoderma* spp. can also be developed as a consortium for the management of soil borne diseases of crop plants.

Screening of Antagonists

All the strains isolated from the different cropping systems have to be ascertained for their virulence and broad spectrum of action against different pathogens that pose a serious economic threat to crops. Selection of an effective strain determines

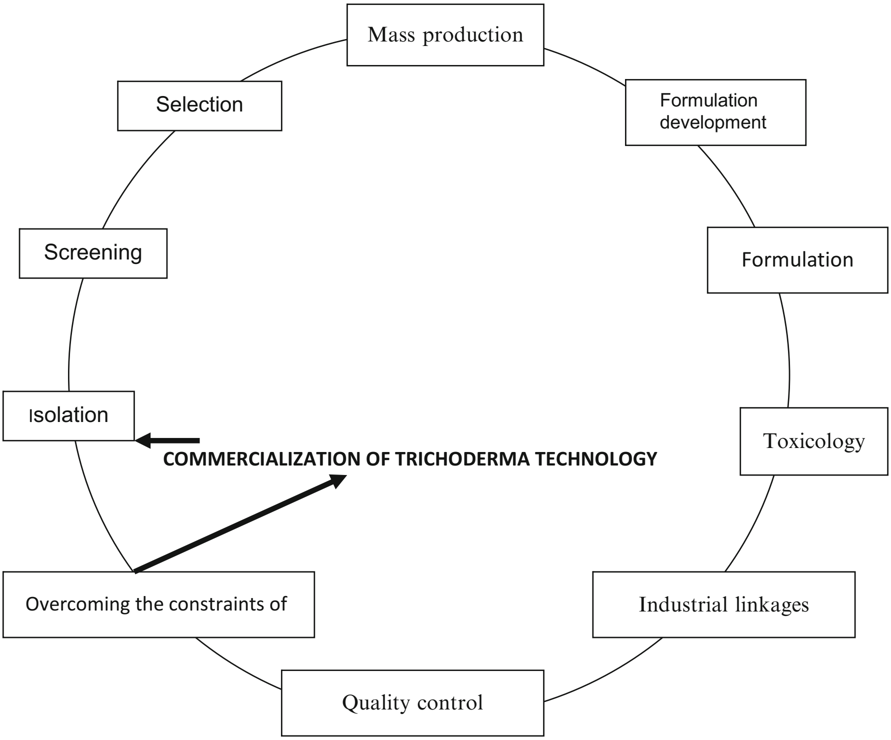

Fig. 4.1 Stages of *Trichoderma* commercialization

the viability of the technology. Hence a proper measurement should be developed to screen the antagonistic potentiality of the biocontrol agents. To be an effective antagonist it should possess a high level of competitive saprophytic ability and antibiosis, should have the ability to secrete an increased level of mycolytic enzymes (chitinases, glucanases, and proteases), be hyperparasitic and promote plant growth. Hence the measurement of efficacy should be developed, comprising of above-mentioned components. Each component should be given weight depending upon their role in disease management. Based on this data an antagonism index should be used to screen for an effective antagonist. This type of rigorous and meticulous screening will lead to the genesis of an effective biocontrol strain that will insure the commercial success of the biocontrol technology.

Pot Test and Field Efficacy of Antagonist

The plant, pathogen, and antagonists are co-exposed to controlled environmental conditions. Exposure of the host to the heavy inoculum pressure of the pathogen along with the antagonist will provide ecological data on the performance of the antagonist under controlled conditions. Promising antagonists identified in controlled environmental conditions are next tested for their efficacy under field conditions along with the standard recommended fungicides. Since the variation in the environmental conditions in the field influence the performance of the biocontrol agent, trials on the field efficacy should be conducted at a minimum of 15–20 locations under different environmental conditions. This is necessary to be able to select the most efficacious candidate for mass multiplication and formulation development.

Mass Production and Formulation of Antagonist

The first major concern in commercial production systems involves the achievement of adequate growth of the biocontrol agent. In many cases biomass production of the antagonist is difficult due to the specific requirement of nutritional and environmental conditions for the growth of the organism. Mass production is achieved through liquid and semisolid and solid fermentation techniques. The commercial success of biocontrol agents requires

- Economical and viable demand
- Consistent and broad spectrum action
- Safety and stability
- Location specific strains
- Increased shelf life
- Low capital costs

Liquid Fermentation

This fermentation system has been adopted for the mass multiplication of fungal and bacterial biocontrol agents. For mass multiplication the selected medium should be inexpensive and readily available with appropriate nutrient balance. Acceptable materials include molasses, corn steep liquor and sulphate waste liquor, and jaggery. Small-scale fermentation in molasses yeast medium resulted in the abundant chlamydospore production. Preparations of *Trichoderma* containing chlamydospores were more effective in preventing the diseases than that of the conidia-based formulations (Papavizas and Lewis 1989).

Solid Fermentation

In nature a wide range of organic substrates with low microbial activity are available and could be used for solid-state fermentation in mass multiplication. A number of composted organic products have been studied for their use as horticultural substrates. These often have to be carefully utilized to remove the toxic substances and may contain pathogenic propagules with a high microbial load. Hence the media with relatively low microbial content would be best suited for solid-state fermentation and beneficial biological amendment. Solid substrates for the production of the inoculum of various biocontrol fungi include straw, wheat bran, sawdust, moistened bagasse, sorghum grains, paddy chaff, farmyard manure and other substrates rich in cellulose.

Semi-Solid Fermentation

This process is used for fungi that do not sporulate in liquid state fermentation. The chances of contamination are high when compared to liquid state fermentation.

Formulation Viability

Shelf life of the formulation determines the commercial success of biocontrol agents. Formulations should support the viable nature of the product for a lengthened storage period. Biocontrol products should have the minimum shelf life of 8–12 months to be commercialized. Carrier material should not affect the viable nature of the biocontrol agent. Commercialization of the bio products is mainly hampered due to the poor shelf life. Hence research should be concentrated on increasing the shelf life of the formulation by developing superior strains that support the increased shelf life, or the organic formulations that support a maximum shelf life with a low level of contaminants. This is necessary to ensure that the biocontrol product results in a successful commercial venture.

Toxicology

Safety and environmental considerations should not be taken for granted and it is crucial that biopesticides are regulated in an appropriate way to conform to international standards. The regulatory environment is generally more favorable for the biopesticides than the chemical pesticides. However, the cost of carrying out the toxicological study for registration is still prohibitive to organizations in developing countries. Toxicology includes information of the antagonist on safety to humans, plants, animals and soil microflora. Cost incurred for the toxicological studies is high and these studies have to be conducted separately for each and every biocontrol organism. The huge investment in the toxicological studies requires linkages between research organizations and private industry.

Industrial Linkages

Research institutes carry out the initial discovery of an effective organism, genetic manipulation of organisms to develop superior strains, and studies on mechanisms, field efficacy and protocols for the development of the formulation. But to take this technology to an entire country or a region requires a partnership between the stakeholders and institutes. Corporate resources are required for the large-scale production, toxicology, wide scale field-testing, registration and marketing. Entrepreneurship may be defined as the exchange of intellectual property for research grants, and a royalty stream, with the establishment of a University – Industry partnership for the benefit of both. The first requirement for the entrepreneurship requires a patent application on the strain and the related technology, especially on the efficacy data, identity of the organism, toxicological data and delivery system. Ideally the process of entrepreneurship will result in an academic corporate research team working towards a common goal, that of promoting IPM and global food security.

Quality Control

This is very much required to retain the confidence of the farmers on the efficacy of biocontrol agents. Being living organisms their population in a product influences the shelf life. The population load of the antagonists determines the minimum level of requirement for providing effective biological control of the plant diseases. Depending on the type of the antagonist (bacteria or fungal), and formulation, the moisture content and population load varies. The other contaminating organisms should also be under the permissible limits.

Constraints to Commercialization

The constraints to biopesticide development and utilization in developing countries mirror some of those factors that limit the development worldwide. Constraints include:

- Awareness, training and education shortfalls
- Lack of multi disciplinary approach
- Technology constraints
    (a) Delivery system
    (b) Biopesticide quality
- Toxicology and Regulatory Matters
- Decline of National and International Research Support

Awareness, Training and Education Shortfalls

The general level of awareness among stakeholders about the potential value of biopesticides pesticides is lacking. There is a need to:

- Increase the awareness level among the policy makers of the potential for biopesticides, their efficacy and their effect in reducing health and environmental problems.
- Promote the opportunities offered by the commercialization in terms of generation of wealth, employment.
- Inform entrepreneurs and investors about the opportunities that exist for establishing commercial companies to manufacture and market biopesticides.
- Train government extensionists in the importance of using biopesticides and the communication between research and extension sectors has to be intensified.
- Explain the nature and mode of action of biopesticides to farmers who are accustomed to using chemical pesticides, which are often fast acting and are visibly effective.

Lack of a Multidisciplinary Approach

The process of biopesticide development requires research in the areas of screening, formulation, field application, production and storage, ecotoxicology, toxicology as well as the steps necessary for commercialization including scaling up production, registration and regulatory matters. Most of the research efforts undertaken with the use of biopesticides are confined only to the exploration, collection, isolation and identification of biocontrol agents combined with laboratory based bioassays. But in the process of product development the above research aspects are only a fraction of the work required to develop a complete product. Product development requires a multidisciplinary approach to biopesticide research and development. Rarely such a complete range of expertise exists in a single institute or organization.

Technology Constraints

Delivery System

Success in biocontrol depends on the understanding and use of delivery systems. The research on delivery systems is well below that of chemical insecticides. Attention to the application technology can improve biopesticide performance.

Bio Pesticide Quality

The major problem in the field of biopesticide production is product quality and stability. In small-scale production, contamination of inoculum is a common problem. The long-term shelf life of the product is highly essential to attract multinational companies to invest on a large scale.

Toxicology and Regulatory Matters

Safety and environmental considerations cannot be taken for granted and it is crucial that biopesticides are regulated in an appropriate way to conform to international standards. The regulatory environment is generally more favorable for biopesticides than chemical pesticides. However the cost of carrying out the toxicological study for registration is still prohibitive to organizations in developing countries. Toxicology includes information on the safety of the antagonist to men, plants, animals and soil microflora. Cost incurred for the toxicological studies is high. These studies have to be done separately for each and every biocontrol organism. Hence, the regulatory issues pertaining to registration of biopesticides should be relaxed so as to popularize the technology as that followed for biofertilizers.

Decline of National and International Research Support

Most policy makers and researchers in developing countries are not fully aware of the usage of *Trichoderma* and biopesticides. Even those who are aware, lack knowledge on the process involved in the isolation and mass production of these agents. In this regard, both National and International support is essential to empower scientists and extension functionaries in terms of knowledge and skill empowerment as is being carried out by the IPM Innovation Lab, a USAID funded program at Virginia Tech, U.S.A.

Strategies to Promote Commercialization

1. Motivating farmers through:
   (a) Publicity
   (b) Field demonstrations
   (c) Farmers meetings
   (d) Biovillage adoption and organizing biocontrol days
2. Conducting periodical training for commercial producers, department functionaries and farmers to increase/improve the supply.
3. Uniform price throughout the country for the product.

Industrial Linkages

- Technical support should be available to entrepreneurs on quality control and for registration with the government insecticide regulatory agencies.
- Preparation of a guidebook on quality control and mass production of biocontrol agents with infrastructure requirement.
- Quality control norms have to be regulated and monitored by State Agricultural Universities, federal/central Institutes so as to produce and supply quality biocontrol agents. Regular monitoring is essential for maintaining quality.
- Constant research support to standardize the dosage, storage, and delivery systems for different biocontrol agents.
- Positive policy support from the government to promote the use of biocontrol agents in crop protection.
- Identification of a separate biocontrol package for organic farming.
- Closer industrial/university linkages with annual stakeholder meetings to promote the quality of biocontrol agents.

Trichoderma spp. for the Management of Various Pathogen Species

Trichoderma species have been widely exploited for the management of seed and soil borne diseases of agricultural and horticultural crops. Soil-borne diseases due to *Rhizoctonia solani*, *Macrophomina phaseolina* and *Fusarium* spp. cause a high percentage of plant mortality, and consequently, high yield losses in rain-fed crops, especially in pulses and oilseeds. Soil incorporation of *T.harzianum* in the field reduced the inoculum density of *R. solani* by 85 % and the fruit rot of tomato by 27–51 % (Strashnov et al. 1985). Soil application of *Trichoderma harzianum* was found effective in reducing the incidence of *Macrophomina* root rot of beans by 37–74 % (Elad et al. 1986). Coating of melon seeds with conidia of *T. harzianum* reduced the disease caused by *Macrophomina* to an extent of 46.3 %. Coating of green gram and cowpea seeds at the rate of 10 g of *T. viride* isolate MG6, combined with soil application resulted in the decrease of dry root rot and increased the yield potential compared to that of untreated control (Nakkeeran and Doraisamy 2001). In addition to disease reduction, dry matter production was also enhanced. This was attributed to the production of growth hormones by the above strain. Treatment of sunflower seeds with *T. viride* at the rate of 4 g/Kg reduced the root rot incidence to 18 % as against 37 % in the control and increased the yield by 21 % (Jeyarajan et al. 1994).

Seed treatment of sesamum with *T. viride* @ 4 g/Kg reduced root rot incidence to 12.8 % and increased the root and shoot length and oil content. It recorded a yield of 677 Kg/ha as against 301 Kg/ha in the control (Sankar and Jeyarajan 1996). Results of *T. viride* demonstrations in farmer's fields in groundnut, sesamum, urdbean, and chickpea against dry root rot indicated promising results in reducing root rot (Jeyarajan et al. 1994).

T. harzianum was found effective in the management of Fusarium wilt diseases. Strain T35 controlled Fusarium wilt of cotton and melon under natural soil conditions (Sivan and Chet 1986). Incorporation of *T. harzianum* as a wheat bran-peat preparation into soil under greenhouse conditions reduced the incidence of crown rot of tomato by up to 80 %. Soil application increased the yield of tomato by 18.8 % (Sivan and Chet 1987).

Soil application of *T. koningii* at the rate of 2 g per vine of black pepper at the time of transplanting was more effective than metalaxyl compounds against Phytophthora root rot. The disease incidence was 23–35 % lower and yield was 30–40 % higher than the control (Georgieva 1991). Pre- and post-planting application of *T. viride* and *T. harzianum* was effective against foot rot disease of betel vine. Amendment of nursery soils with *T. harzianum* prior to the colonization of the damping off pathogen in nursery beds resulted in the reduction of pre- and post-emergence damping off of cardamom (Bhai and Thomas 1998). Delivery of *Trichoderma* strains through solid matrix priming in tomato and chilies reduced the damping off incidence, under field conditions, more than that of dry seed treatments (Nakkeeran and Doraisamy 2001).

Spread of *Trichoderma* Technology

International workshops on the production and use of *Trichoderma* and *Pseudomonas* were organized with the financial assistance of the IPM Innovation Lab and conducted at Tamil Nadu Agricultural University, Coimbatore, India; Nepal by International Development Enterprises (iDE); World Vegetable Center, Arusha, Tanzania; and the Royal University of Agriculture, Phnom Penh, Cambodia from 2011 to 2015. Scientists and stakeholders from Bangladesh, Cambodia, Ethiopia, Ghana, Guatemala, Honduras, India, Indonesia, Kyrgyzstan, Kenya, Malaysia, Nepal, Rwanda, Senegal, Tanzania, Uganda, and Uzbekistan were trained on the following aspects pertaining to *Trichoderma* and *Pseudomonas*:

- Significance of biopesticides in plant disease management.
- Isolation of *Trichoderma* and *P. fluorescens* from rhiizophere soil.
- Selection of *Trichoderma* and *P. fluorescens*.
- Phenotypic characterization of *Trichoderma* and *P. fluorescens*.
- Mass production of *Trichoderma* and *P. fluorescens*.
- Delivery systems and shelf life of *Trichoderma* and *P. fluorescens*.

- Registration protocols of biopesticides.
- Hands on training on isolation, selection, screening and mass production of biocontrol agents.

Field demonstrations were conducted on the use of biocontrol agents to popularize the technology in Tamil Nadu, India through IPM Innovation Lab collaboration. After the hands on training, the participants produced their own biopesticide products for the management of diseases of crop plants.

Commercial Bio-products of *Trichoderma* spp.

Table 4.3 lists the *Trichoderma* spp. available for the management of various pathogen species and Table 4.4 lists the commercial products of *Trichoderma* spp. that are available for the management of soil–borne diseases. They are available in the form of wettable powders, granules, sticks, crumbles, pellets etc.

Table 4.3 *Trichoderma* spp. for the management of various pathogen species

Antagonist	Pathogen/disease	Host	Method of application	Reference
Trichoderma sp. C62	*Sclerotium cepivorum*	Onion	Soil application as bran sand inoculums	Kay and Stewart (1994)
Trichoderma spp.	*G. graminis* var. *tritici*	Wheat	Spores added to soil	Ghisalberti et al. (1990)
				Coley-Smith et al. (1991)
	R. solani	Lettuce		Lewis et al. (1991)
		Lettuce		
T. harzianum	*Fusarium graminearum*	Radish	Soil	Fernandez (1992)
T. harzianum T95I	*Pythium ulktimum*	Cucumber	Soil	Paulitz et al. (1990)
T. koningii	*S. rolfsii*	Tomato	Soil	Latunde-Dada (1993)
T. koningii	*Pythium* spp.	Chickpea	Seed	Lifshitz et al. (1986)
	Pythium spp.	Pea	Seed	
	P. ultimum	Pea	Soil	
T. harzianum	*P. ultimum*	Cotton	Seed	Harman et al. (1989)
		Maize	Seed	
		Pea	Seed	
T. harzianum + *Rhizobium*	*S. rolfsii*	Groundnut	Seed and soil	Muthamilan and Jeyarajan (1996)

(continued)

Table 4.3 (continued)

Antagonist	Pathogen/disease	Host	Method of application	Reference
T. viride	*M. phaseolina*	Sesamum	Seed	Sankar and Jeyarajan (1996)
T.harzianum				
T. longibrachiatum				
T. viride	*M. phaseolina*	Groundnut	Seed	Jeyarajan et al. (1994)
		Sesamum		
		Blackgram		
		Greengram		
		Pigeonpea		
		Sunflower		
T. hamatum	*R. solani*	Cotton	Soil-as mycelial preparations	Lewis and Papavizas (1986)
		Sugarbeet		
		Radish		
T. viride	*M. phaseolina*	Blackgram	Seed	Raguchander et al. (1997)
T. viride	*M. phaseolina*	Greengram	Furrow application	Raguchander et al. (1998)
T. viride	*F. udum*	Pigeon-pea	Seed and soil	Nakkeeran et al. (1995)
	M. phaseolina			
T. viride	*F. oxysporum f.* sp. *cubense*	Banana	*Trichoderma* capsules	Nakkeeran et al. (1996)
			Seed	Nakkeeran and Doraisamy (2001)
	R. solani	Cotton	Seed	
		Green gram	Seed + soil	
	M. phaseolina	Cowpea		
	Pythium ultimum	Chilies,		
		Tomato		
Trichoderma spp.	*M. phaseolina*	Sesamum	Seed	Dinakaran and Marimuthu (1997)
		Blackgram	Seed and soil	
T. viride	*R. solani*	Cotton	Seed	Mathivanan et al. (2000)
	S. rolfsii	Brinjal Sunflower		
		Bhendi		

Table 4.4 Commercial bio-products of *Trichoderma* spp. available for soil borne species

S.no.	Product	*Trichoderma* spp.,	Function	Crop	Manufacturer/country
1	AkTRIvator	*T. harzianum* 002/003	Promote growth; suppress soilborne pathogens; stimulate root development; cited for use in hydrophonic systems	–	Canna, The Netherlands/U.K.
2	ArborGuard	*Trichoderma* sp.	Promote growth; suppress *Armillaria* spp.	Forestry seedlings	Bio-protection Research Centre, Lincoln University, New Zealand
3	Binab line	*T. atroviride* ATCC 20476 and	Tree wound pathogens	Ornamental shade and forest trees	Binab Bio-Innovation AB, Sweden
	Binab T				
	Binab Golf	*T. parapiluliferum* IMI 206039			
4	Biobus 1.0 WP	*T. viride*	General topical mycoparasite	Many crops including citrus, coffee, potato, mango, tomato, cabbage	Nam Bac Co., Ltd., Vietnam
5	Bio-Cure-F	*T. viride*	General mycoparasite applied topically as seed dressing and soil drench	General vegetable crops	T. Stanes & Co., India
6	Bioderma	*T. viride*	Wide spectrum mycoparasite against root and leaf pathogens; stimulate seed germination	Cotton, cereals, pulses, vegetables, oilseeds, fruit plants, floriculture	Biotech international Ltd., India
7	Bioderma-H	*T. harzianum*	Wide –spectrum mycoparasite against root and leaf pathogens;stimulate seed germination	Cotton, cereals, pulses, vegetables, oilseeds, fruit plants, floriculture	Biotech international Ltd., India
8	BioHealth TH	*Trichoderma* sp. T-50	Soilborne pathogens; Promote plant growth; seed and foliar treatments	Wide range of crops,including vegetables,ornamentals, turfgrass, cereals	Humintech GmbH, Germany
	WSG				
9	Bio-Humaxin SenVang 6SC	*Trichoderma* spp.	Applied as seed treatment and in potting mixtures	Crops not specified	Cong Ty TNHH An Hung Tuong, Vietnam

(continued)

Table 4.4 (continued)

S.no.	Product	*Trichoderma* spp.,	Function	Crop	Manufacturer/country
10	Biospark Trichoderma	*T. parceramosum*	Promote growth;biofungicide;activator for rapid composting; control damping off caused by *Phytopthora* spp., and *Rhizoctonia solani*; controls mango gummosis;control durian dieback caused by *Phytopthora* spp.	Rice, corn, mango, durian, vegetable crops, organic composting	Biospark crop., Philippines
11	Bio Tam (U.S.A)	*T. asperellum* ICC 012+*T. gamsii* ICC 080	Controls a broad spectrum of soil borne pathogens, including Basidiomycetes, Ascomycetes and stramenopiles	Various	AgraQuest, U.S.A.
12	Bioten (Spain)	*T. asperellum* ICC 012+*T. gamsii* ICC 080	Control a broad spectrum of soil borne pathogens, including Basidiomycetes, Ascomycetes and stramenopiles	Various	Isagro S.P.A., Italy
13	Eco-SOM Bio-Cure F Trieco	*T. viride*	Promote root growth, suppress the soil borne pathogens *Botrytis* spp., Pythium spp., *Sclerotium* spp., *Fusarium solani*, *Sclerotinia homoeocarpa*	Various	Ecosense Lab. India
14	Fertisain	*T. harzianum*	Enzymatic extracts stimulate photosynthesis; stimulate resistance against foliar pathogens; increase leaf surface	Vegetables, grapes	Biophytech, France
15	Fulhumaxin 5	*Trichoderma* spp.	Fungicide; control black spot, rust, powdery mildew	Various	Cong Ty TNHH An Hung Tuong, Vietnam
16	Lettucemate Flake and Drench WP	*T. hamatum*	Plant health; seedling mix and seedling drench	Lettuce	Agrimm Technologies, New Zealand
17	Naturall	*Trichoderma* sp.(+bacteria)	Plant health	Various	Advanced Biological Marketing, U.S.A.

18	NLU-Tri	*T. virens*	Plant health; antagonist	Various	Ho Chi Minh University of agriculture and forestry, Vietnam
19	Plantmate Drench	*T. harzianum*	Root zone drench; root zone starter granule; enhance root development	Various	Agrimm Technologies, New Zealand
	Plantmate Granular				
20	Plantmate Foliar	*T. atroviride+T. harzianum*	Foliar spray; Plant health; micronutrient uptake	Various;cutflowers	Agrimm Technologies, New Zealand
21	Plantsain	*T. harzianum*	Aromatic extract to clear vascular tissue of pathogens; solubilize iron, copper, manganese	Vegetable crops	Biophytech, France
22	PlantShield	*T. harzianum* T-22	Biofertilizer; drought resistance	Various	Bioworks,Inc., U.S.A.
23	Promot WP	*T. harzianum* + *T. koningii*	Promote growth, suppress soil borne pathogens	Annual and perennial crops	SW-Dungesysteme GmbH, Germany
24	Pusa 5 SD	*T. virens*	Seed coating to protect against *Rhizoctonia solani*	Mungbean, chickpea	Indian Council of Agricultural Research, India
25	Radix (Italy)	*T. asperellum* ICC 012+ *T. gamsii* ICC 080	Control a broad spectrum of soil borne pathogens including Basidiomycetes, Ascomycetes and stramenopiles	Various	Isagro S.p.A., Italy
26	Remedier	*T. asperellum* ICC 012+ *T.gamsii* ICC 080	Control a broad spectrum of soil borne pathogens including Basidiomycetes, Ascomycetes and stramenopiles	Various	Isagro S.p.A., Italy
27	Rhizoderma	*T. harzianum* Th2	Seed treatment to control *Bipolaris sorokiniana*, *Derchslera tritici-repentis*, *Fusarium graminearum*	Wheat, barley	Rizobacter Argentina S.A., Argentina
28	Rootmate	*T. virens* G41	Promote plant health; control *Pythium* stem and root rot; drench on seedlings	Ornamentals, forest trees	Bioworks,Inc., U.S.A.

(continued)

Table 4.4 (continued)

S.no.	Product	*Trichoderma* spp.,	Function	Crop	Manufacturer/country
29	Root –Pro	*T. harzianum* Th2	Control *Pythium* spp.,*Sclerotium rolfsii*., *Fusarium* spp., at the nursery stage	Various	Agriance, Israel
30	RootShield	*T. harzianum* T -22	Biofertilizer; drought resistance suppress soil borne pathogens *Fusarium* spp., *Pythium* spp., *Rhizoctonia* spp.	Greenhouse crops, outdoor nursery plants, greenhouse transplants, ginseng	Bioworks,Inc., U.S.A.
31	SabrEx PB and SabrEx HC Root Inoculant	*Trichoderma* sp.	Stimulate growth; planter box treatment and seed treatment	Corn, cotton, wheat, other cereals	Advanced Biological Marketing, U.S.A.
32	Sentinel	*T. atroviride*	Bioprotectant;foliar spray against *Botrytis* spp.	Various	Agrimm Technologies, New Zealand
33	Sim Derma	*T. harzianum* Kuen 1585	Soil borne pathogens including *Fusarium* sp., *Pythium* sp. and *Rhizoctonia* sp.	Wheat, onion	Simbiyotek, Turkey
34	SoilGard	*T. virens* G1-21	Promote root development, stimulate resistance to soil borne pathogens, soil application to promote root development, solubilize phosphorus, promote resistance to, *Pythium sp.*, *Rhizoctonia sp*. and *Sclerotinia sp.*	Melons, leafy greens, greenhouse ornamentals	Certis, U.S.A.
35	Solsain S	*T. harzianum*		Fruits, vegetables, grape	Biophytech, France
36	Supresivit	*T. harzianum* Kuen 1585	Stimulate plant growth	Strawberry, tomato	BioPlant, Denmark
37	T 34	*T. asperellum* T-34	Root and foliar applications, antagonist and stimulate growth and resistance, control *Botrytis* sp., *Fusarium* sp. and *Sclerotinia* sp.	various	Biocontrol Technologies S.L., Spain

38	Tenet (New Zealand)	*T. atroviride*	Control onion white rot (*Stromatinia cepivora*), *Fusarium* basal rot	*Allium* spp.	Agrimm Technologies, New Zealand
39	Tenet (U.S.A)	*T. asperellum* ICC 012+*T.gamsii* ICC 080	Control a broad variety of soil borne pathogens including Ascomycetes and Basidiomycetes	Various	Isagro U.S.A.; Isagro Italy
40	Tory	*T. harzianum* YC 459	Antagonist, foliar application against botrytis grey mould	Cucumber, tomato	JGreen,Inc., Korea
41	Trianum-P	*T. harzianum* T-22	Biofertilizer, drought resistance	Various	Koppert B.V., Netherlands
	Trianum-G				
42	TRi B_1	*Trichoderma* sp.	Soilborne diseases	Crops not specified	Institute of Plant Protection, Vietnam
43	Trichobiol	*Trichoderma* sp.	Promote plant growth antagonistic to *Armellaria* sp., *Botrytis* sp., *Fusarium* sp., *Phytophthora* sp., *Pythium* sp., *Rhizoctonia* sp., *Rosellinia* sp. and *Sclerotium* sp.	Various	Bioecologicos Agricolas, Colombia
44	Trichodex	*T. harzianum* T-39	*Botrytis cinerea*	Various	Makheteshim Agan of North America,Inc., U.S.A.
45	Trico-DHCT	*Trichoderma* spp.	Foliar application to control gold leaf rot of citrus, soil application to control soil borne pathogens including *Fusarium solani*	Citrus, melons, rice	AGPPS,Vietnam; Can Tho University, Vietnam
46	Trichodry	*T. atroviride*	Stimulate plant health, root zone starter flake in growing media	Used in all bark-and peat-based growing media	Agrimm Technologies, New Zealand
47	Trichoflow	*T. atroviride*	Stimulate plant health, root zone starter WP	General use, including nursery, greenhouse, turf, orchards, vineyards	Agrimm Technologies, New Zealand
48	Trichopel	*T. atroviride*	Stimulate plant health, root zone starter granule	General use including nursery, bulbs, tubers, vines, trees	Agrimm Technologies, New Zealand

(continued)

Table 4.4 (continued)

S.no.	Product	*Trichoderma* spp.,	Function	Crop	Manufacturer/country
49	Trchosan	*T. harzianum*	Induce resistance, promote growth	Various	Sautter and Stepper, Germany
50	Trichospray	*T. atroviride*	Stimulate plant health, foliar booster WP	Foliage, flowers	Agrimm Technologies, New Zealand
51	Tusal	*T. harzianum* +*T. viride*	Mycoparasite against soil borne pathogens, including *Colletotrichum* sp.	Cucurbits, strawberry, *Capsicum* spp., sugarbeet seed, tomato	Certis, Spain
52	Unite WP	*T. atroviride*	Bioprotectant against damping off and root rot disease, including *Cylondrocarpon* sp., *Phytophthora* sp., *Pythium* sp., *Rhizoctonia* sp., root zone drench	General use	Agrimm Technologies, New Zealand
53	VI-DK	*Trichoderma* sp.	Mycoparasite against soil borne pathogens	Tomato, beans, potato, tobacco, durian, melon, *Capsicum* spp.	VIPESCO, Vietnam
54	Vinevax	*T. atroviride*	Bioprotectant against *Armillaria* sp. and die back pathogens, wound dressing and injection	Kiwi, grapes, orchard crops	Agrimm Technologies, New Zealand
55	Vitalin	*T. harzianum*	Strengthen plant, suppress soil borne pathogens	General use	Vitalin Pflanzengesundheit GmbH, Germany
56	Vitalin MX5	*T. harzianum* *T. hamatum* *T. koningii*, *T. reesei* *T. virens*	Strengthen plant, suppress soil borne pathogens and *Botrytis* sp.	General use	Vitalin Pflanzengesundheit GmbH, Germany

Conclusion

The decades of laboratory research has moved the use of *Trichoderma* spp. from the lab to farmers' fields. It would be unrealistic to expect that *Trichoderma* would replace chemical fungicides in disease control if they do not have the long shelf life equivalent to chemical pesticides. Future research should be directed towards exploiting *Trichoderma* spp. in disease control. Evaluations should be conducted to determine whether a combination of several strains would perform better than a single strain in the management of both seed and soil-borne diseases. An advantage of biological agents is that they act through a variety of mechanisms, thus avoiding the development of resistance by pathogens to their activity.

Future research should address the knowledge needed to improve the genetic potential of the organisms which could be utilized to develop strains with a broad spectrum of action against several plant pathogens. In addition appropriate delivery systems need to be developed that provide, effective and environmentally sound biological control in a wide range of applications in both greenhouse and open field cultivation of agricultural and horticultural crops. Besides, policy makers should be enlightened to relax the norms related to registration of *Trichoderma* spp., for large scale adoption and horizontal spread of the technology.

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Chapter 5
Physical, Mechanical and Cultural Control of Vegetable Insects

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Abstract Pest control is as old as agriculture, as there has always been a need to keep crops free from pests in order to maximize food production. Historically, mechanical and cultural practices were the major methods used by farmers to prevent crop losses. Prior to the emergence of the plant protection sciences farmers evolved many cultural practices through trial and error experiences to minimize the damage caused by insect pests. In recent years pesticides have become the major method of pest control. Due to the problems related to the use of pesticides physical, mechanical and cultural controls serve as an alternative to the use of pesticides in an integrated pest management approach. Physical methods consist of thermal methods and electromagnetic radiation. Mechanical control refers to measures that involve the operation of machinery or manual operations such as the hand picking of insects from plants. Cultural control consists of modifications of standard agricultural practices such as time of planting and crop rotation. Examples of physical, mechanical and cultural control methods employed in the management of tropical vegetable pests and diseases are herein discussed.

Keywords Electromagnetic radiation • Crop rotation • Trap cropping • Technology transfer

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Introduction

Vegetables are important sources of vitamins, minerals, plant proteins and other elements which are essential for human health throughout the world (Fowler 2011). Despite the importance of vegetables, the cultivation of vegetables is constrained by biotic stresses including insect pests. Significant losses in quantity and quality caused by insect pests have been reported by several workers. The use of insecticides is the most common component of insect pest management in vegetables. However, prolonged use of several synthetic insecticides caused development of heritable resistance to insecticides in more than 540 species of insect pests (Metcalf et al.1994). In addition, the resurgence and outbreak of secondary pests, harmful effects on non-target organisms and potential effects of pesticides on human health and the environment have been widely reported and documented (Metcalf and Luckmann 1994; Novartis 1997). In order to overcome these problems interest has been revived in the search for alternative and sustainable pest control methods. Integrated Pest Management (IPM) is the integration of two or more pest control tactics into one program and is considered an environmentally acceptable and economically profitable means of managing insect pests. Physical, mechanical and cultural control methods hold promise from pre- to post-harvest situations of the crop (Vincent et al. 2003). This chapter emphasizes the physical, mechanical and cultural control of insect pests on tropical vegetables.

The information on passive and active methods of physical controls by Charles Vincent, Guy Hallman, Bernard Panneton and Francis Fleurat-Lessard is a classic and well summarized in the 2003 Annual Review of Entomology titled “Management of Agricultural Insects with Physical Control Methods” and modified and supplemented with cultural control methods (Metcalf et al.1962, 1994; Metcalf and Luckmann 1994; Pfadt 1971; Ross 1967; Sorensen 2000). These references together provide a total and complementary approach to insect pest control and management on vegetable and related crops (Sorensen and Baker 1994). The Vincent et al. 2003 review (Vincent and Chagnon 2000) complemented earlier work of Banks (1976), Hallman and Denlinger (1998), Oseto (2000), and Vincent et al. (2001) and offered a critical assessment of physical controls with the objective of formulating recommendations for further research and applications. This chapter provides an integrated approach and summary of the current literature on physical, mechanical and cultural control methods and how they are used in vegetable production. It also offers some expanded opportunities in IPM in vegetables and how they and others might be used in developed and in developing tropical ecosystems (Rabb and Guthrie 1970; Sorensen 1977, 2008).

Physical Control

Physical methods aim to reduce pest populations by using devices that physically affect pests or affect their physical environment (Dhaliwal and Arora 1996). Physical control methods modify the physical environment of insect pests and thus minimize their threat to agricultural crops. The result ranges from agitation to death of these pest insects, as many physical control methods affect the physiological and behavioral processes of insect pests. Physical control methods give immediate and effective control of insect pests from emergence to post harvest (Hallman 2000) and the methods are popular and accepted by farmers. Physical control consists of thermal methods and electromagnetic radiation.

Thermal Methods

(i) **Temperature** (both high (Fleurat-Lessard and Le Torc'h 2001) and low temperatures (Fields 2001)) can be effective to reduce the population of insect pests and is used postharvest to slow degradation of produce caused by physiological processes, pathogens, and insect pests. In insect control both temperature and rate of changes and duration of exposure must be considered (Duchesne et al. 2001).

(ii) **Cold storage**: The oldest and most widely used quarantine treatment is storage of fresh commodities of vegetables and others at −0.6° to 3.3 °C for 7–90 days, depending on nature of the produce, insect pest status and temperature (APHIS 1998).

(iii) **Heated air**: Quarantine treatments using heated air were first used against the Mediterranean fruit fly infestation in Florida in1929. These treatments expose commodities to air at temperatures in the range of 43–52 °C from a few to many hours. Preconditioning vegetables with a mild heat treatment prior pesticide treatment reduces damage to commodities (Hallman 2000; Hara et al.1997).

(iv) **Hot-water immersion**: Immersion at 43–55 °C ranging from a few minutes to a few hours is used to kill a variety of arthropods and nematodes on plant-propagative materials (yam, colocasia, etc.). Hot-water immersion is simple, economical, and rapid method for disinfestation of plant materials from insect pests. A variation with hot-water immersion is a hot-water drench, which appears to cause less damage to vegetables than total immersion (Bollen and DelaRue 1999).

(v) **Steaming**: It affects insect legs when exposed to temperatures from 68 to75 °C. Leg muscles are inactivated by dipping insects from 0.2 to 0.4 s in hot water. Steaming in laboratory and field conditions impaired locomotion of only 35 % of Colorado potato beetle adults when used at the maximum acceptable temperature for the potato plant (Pelletier et al. 1998).

Electromagnetic Radiation

Electromagnetic radiation energy is absorbed by ionizing atoms or by inducing vibration of charged particles within the matter thus increasing temperature because of internal frictions (Lewandowski 2001).

(i) **Irradiation**: Ionizing radiation provided by cobalt-60, cesium-137, or linear accelerators are an effective commercial quarantine treatment (Hallman 2000). Radiation is effective by providing sterility at doses tolerated by fresh commodities.

(ii) **Reproductive**: Reproductive control in insects has been most effective where it has been developed and used against flies and is receiving much attention with moths, beetles and weevils. This method renders males sterile but still active. Rearing and releasing these gamma radiated males, in greater numbers than exist in the natural population, is extremely expensive. A group of organic compounds called chemosterilants also produce varying degrees of sterilization in insects and continues to receive attention. Efforts to manipulate the sex determining apparatus of a species so that few females are produced are a part of genetic engineering (Pfadt 1971; Ross 1967).

(iii) **Radio frequency heating**: The radio frequency (RF) part of the electromagnetic spectrum produces non ionizing waves which transfer energy faster and more efficiently than heated air or water treatments. Although RF energy kills insects and much research has been conducted on its effects (Hallman and Sharp 1994; Halverson et al. 1997; Nelson 1995), it has rarely been used on a commercial scale.

Mechanical Control

Mechanical control refers to measures that involve the operation of machinery or manual operations. It is the management and control of pests using means such as fences, barriers or traps. It results in the reduction of or suppression of insect populations.

Barriers may be any living or non-living materials used for restricting pest movement or to delineate a confined space. They are compatible with other control methods (Boiteau and Vernon 2001) and are degradable or non-degradable barriers that can be dismantled and possibly reused to help lower cost. But establishing barriers incur a cost for labor and storage.

An obvious physical barrier is a glass, plastic or screened green house. An additional partial barrier is the use of plastic in raised beds and in low and high tunnels where the ends are open. Nursery beds covered with polythene sheets of 45 gauged (0.45 mm) thickness for the period of 3–4 weeks significantly reduce the incidence of soil borne insect pests and their damage. Row covers have also been used to protect plants from direct insect pest attack or from vectoring plant diseases (Sorensen 1978–80b). All of these methods protect plants from insect pests by prevention or delay of insect pest attack and subsequent economic damage.

Screening of green houses or plant beds will keep out some insect pests. Of course they can also keep insect pests in the screen housed along with some natural enemies (parasitoids and predators) should they be introduced (Sorensen 1991, 1997). Individual plants or fruit and plant beds can be screened with thin cloth or netting. Sticky bands around small plants or collars around plants or chips under melons, hot kaps, and shingles on soil around plants and use of other devices can provide hiding places for pest insects and attract them where they can be crushed. This prevents or slows down insect establishment and economic damage (Sorensen 1991, 1996, 1997). The destruction of insects or egg masses by hand is practical where cheap labor is available and where the insect or eggs are large, not too active or occur in relatively restricted or small areas. Mechanical devices such as hopper dozers, hopper catches, aphid dozers, fly traps, moth traps maggot traps, light traps, electric traps and entoleters can be used with some to total effectiveness.

(i) **Hand collection and destruction**: Handpicking is the most ancient method of mechanical control of egg masses, larvae and adults of several insect pests. This includes the tomato fruit borer (*Helicoverpa armigera*) infested plant materials and egg masses of *Spodoptera litura* on leaf surfaces and reduces further incidence and damage.

(ii) **Cleaning**: Cleaning is a most common pre and post-harvest treatment and as a quarantine treatment, is followed by inspection and by another treatment. Soapy water and wax treatment were used against the false spider mite in Chile. It consists of immersion of cherimoyas (*Annona cherimola*) and limes in soapy water for 20 s, a rinse and then immersion in a wax coating (APHIS 1998).

(iii) **Sound**: Sounds at frequencies <20Hz can be defined as infra sound, and ultra sound at frequencies higher (>∼16 kHz) than human audibility (Sorensen 2008). All insects contain microscopic gas bodies that can oscillate under the influence of ultra sound and abnormal development of *Drosophila melanogaster* resulted from these oscillations (WHO 1982). As ultra sound transmits well through water, its use in postharvest, while produce is being washed by immersion in water, was tried on asparagus spears for thrips with negative results (Van Epenhuijsen et al. 1997).

(iv) **Pneumatic**: Insect pests can be dislodged from plants using blown or aspirated air, but blown insects must be collected and destroyed (Khelifi et al. 2001). Success has been reported on Colorado potato beetle (Lacasse et al. 2001; Vincent and Boiteau 2001), leaf miners on celery, and whitefly on melons (Vincent and Boiteau 2001).

Trenches or Ditches

Trenches to intercept walking insects such as the chinch bug were implemented as early as 1895 (Metcalf et al. 1962; Ross 1967). Studies conducted 100 years later on potato in the northern temperate zone support the effective use of V-shaped ditches, either plain or lined with plastic. These ditches can retain overwintering populations of adult Colorado potato beetles (Ferro 1996; Metcalf et al. 1962; Misener et al. 1993). Crawling hordes of insects can be stopped with deep ditches around fields toward which they are walking. Use of barrier lines of certain heavy-bodied oils poured along the ground and low fences of sheet metal, and V-shaped ditches to control some beetles or weevils for a limited period of movement have been somewhat effective (Pfadt 1971; Ross 1967).

Fences

Fencing has been effective for excluding low-flying insects (e.g., anthomyiids and thrips) from annual crops where few insecticides are registered and the crop value is high (e.g., onion and cole crops) (Boiteau and Vernon 2001). In tomato, the use of 100 mesh nylon nets in nursery prevents the entry of whiteflies *Bemisia tabaci* and their transmission of leaf curl disease.

Organic Mulch

Organic growers have had success with straw mulch as it indirectly affects the Colorado potato beetle population and significantly reduces the damage (Ferro 1996; Yepsen 1977) by favoring several species of egg and larval predators. The use of mulch must be prior to peak emergence of moths (Sorensen 1972–82, 2005a, b). Proper mulching and irrigation helps to reduce population buildup of major insect and mite pests in vegetable cultivation (Srinivasan 2016).

Mulches from Artificial Materials

Paper or plastic sheets or aluminized films can be used for mulching and provide insect control directly or indirectly by preventing feeding by insect vectors of several plant viruses. Plastic mulches of different colors modify the spectrum of incident light and alter the behavior of insects and confuse the insects in flight and landing. Thrips are attracted to blue, black, and white (Sorensen 2002), aphids to yellow and (Black 1980; Csizinsky et al. 1990) and *Spodoptera litura* to blue. Aluminized materials can attract some insects and repel others (Bégin et al. 2001; Jackson et al. 1998). These are sometimes called a push or pull method of insect management. UV-reflective mulches have been used in the management of insect pests on pepper and tomato (Kring and Schuster 1992). Artificial mulches also interfere in the growth and development of weeds, insect pests, plant diseases and nematodes, and also enhance yields (Bégin et al. 2001; Vincent et al. 2001).

Aluminum reflective strips or paint on the shoulder beds of black plastic provide effective management of aphid vectored *Watermelon mosaic virus II*. The virus development was delayed and fruit symptoms appeared several weeks later and bountiful harvests of clean fruit were obtained. The aluminum strip or paint/black plastic provided satisfactory control until the squash plant covered the entire bed (Sorensen 1978–80b).

Trapping

As a management tool, perimeter trapping has been successful in intercepting flying dipterans. Monitoring and mass trapping with sticky traps with protein bait of different colors has been effective for trapping dipteran adults on cabbage (Sorensen and Baker 1994). Seed corn maggot adults and cucumber beetles have been monitored and captured in large numbers on cucumbers with some success. Aphids, leafminer flies, thrips and other soft bodied insects and natural enemies have also been collected on sticky traps (Fig. 5.1). Tedders black pyramidal traps have been effective in monitoring pecan weevil emergence for the purpose of timing sprays and to provide some mass trapping action (Sorensen 1996). Yellow sticky cups have been inverted and staked to monitor and forecast several insect pests (aphids, flea beetles, thrips wireworm adults, Japanese beetles) and some of their natural enemies on sweet potato (Fig. 5.2) (Sorensen 2002, 2008). Sticky traps, treated with various insecticides, placed in the field overnight to collect tomato pinworm moths, and then brought back to the lab, have been used to determine insecticide resistance levels (Schuster et al. 1996). Use of yellow pan/sticky traps @ 10 per ha help to reduce the sucking pest populations. Installation of sex pheromone traps @ 12 per ha can be used to monitor the population of *H. armigera*, *S. litura* and *Earias* spp. (Hamed and Nadeem 2010).

Fig. 5.1 Sticky traps with soft bodied insects

Fig. 5.2 Sweet potato weevil trap

Oils, Soaps, and Surfactants

Oils and soaps (2 %) have been used over many years to control scale insects, aphids, mites and borer eggs. MPede is a commercial soap that is widely used against soft bodied insects of several crops that require frequent spray with a day pre-harvest interval between last application and harvest (Sorensen 1991, 1997; Sorensen and Baker 1994). It is here, and with organic production of vegetables, that safe products like MPede and others are being developed for niche markets. These oils affect the respiratory system of adult insects and mites or their immature stages, particularly eggs. In some cases they act as an oviposition deterrent. Arthropods affected include mites, scale insects, mealybugs, psyllids, aphids, leafhoppers and some lepidopteran eggs. SilwetL-77 is an organo-silicone molecule that has insecticide effects and has activity against the diamond back moth on crucifers (Gauvrit and Cabanne 2002; Shapiro et al. 1998).

Cultural Control

Simple modifications of a pest's environment or habitat often prove to be effective methods of pest control. As a group, these tactics are usually known as cultural control practices because they frequently involve variations of standard agricultural practices. Cultural control is the reduction of insect pest populations on crops by use of agricultural practices which makes the environment unfavorable for insect pests

(Metcalf et al. 1962; Pfadt 1971; Sorensen 1977, 1987, 2000; Westcott 1964). Cultural control measures differ from physical or mechanical control in generally involving the use of ordinary farm practices and farming machinery and in being preventive, indirect or not measureable, so one does not know how effective they really are. They are used in advance of insect damage, so they are more preventive than cure. They are economical and especially effective against pests of low value crops. Results from cultural practices effects the weak point in the pest insect's life cycle or adaption to the environment (Pfadt 1971; Ross 1967). Hence, it is critical that one understand the life history and habits of specific insect pests (Sorensen and Baker 1994).

Since these control tactics usually modify the relationships between a pest population and its natural environment, they are also known, less commonly, as ecological control methods. Simplicity and low cost are the primary advantages of cultural control tactics, and disadvantages are few as long as these tactics are compatible with a farmer's other management objectives (high yields, mechanization, etc.). They are economical and especially effective against pests of low value crops.

Cultural control includes sanitation, destruction of crop residues and weeds, burying infested fruit in holes, covering or using screens over the top vegetative portions to prevent insects from escaping, burning crop residues after harvest, and keeping fields and areas surrounding field clean by hand removal or use of chemicals to destroy weed or alternate wild hosts where insects may survive until the next planting of crops (Metcalf et al. 1962; Pfadt 1971; Ross 1967). The following practices are employed in vegetable pest management.

Preparatory Cultivation

Prevention is better than the curative methods thus the preparatory cultivation methods including clean cultivation, systematic pruning of infested plant parts play a vital role in the control of insect pest populations. Clean cultivation is recommended for *Hellula undalis* because it feeds and develops on certain weeds such as *Cleome rutidosperma* and *C. viscosa*, which act as alternate hosts during the off seasons. Proper cutting and removal of infested plant parts of eggplant help to reduce the incidence of *Leucinodes orbanalis* and some sucking pests (mealy bugs) (Alam et al. 2003).

Tilling or Cultivating Soil

Tilling or cultivating the soil by altering the texture of soil and the chemical composition, the percentage of soil moisture, temperature and soil organisms can adversely affect the growth and development and survival of insect pests. This is the case with soil borne insect larvae or where pupation occurs in the soil (Metcalf et al. 1962; Pfadt 1971; Ross 1967; Westcott 1964; Yepsen 1977). Racking up and hoeing of the soil around melon plants and other vegetables is effective.

Flooding

Flooding is a method to drive out the hibernating larvae and other stages of insect pests. It is a standard agronomic practice to control soil borne insect pests. Soil pupating, leaf consuming lepidopteran larvae (*S. litura* and *S. exigua*), can be controlled by flooding the field.

Overhead Irrigation

Overhead irrigation of water cress at night reduced the number of eggs laid by the diamond-back moth. This has been observed in collard production as well (Tabashnik and Mau 1986). Overhead watering also decreases codling moth, flight, oviposition and egg and larval survival (Prokopy and Croft 1994).

Crop Rotation

Changing or rotating crops in different families can help to control insect pests (Metcalf et al. 1962; Pfadt 1971; Ross 1967; Sorensen 1977; Westcott 1964; Yepsen 1977). Insects reduced by rotations have a long life cycle, a limited host range and are immobile in one stage of development. Changing crops isolates pests from their food supply. Planting the same crop or crops in the same family or relay planting the same crops before the previous crop is harvested increases insect pest populations and their damage. Rotations are more effective in agronomic crops than in horticultural crops like fruit and vegetables. Also be aware of alternate wild host plants or volunteer plants from the previous crops that exist near, as they serve as reservoir hosts to infest your later plantings.

Rotation of crops from year to year will help to destroy insect pests specific to some crops over others (Weber et al. 1994). Among the insects that injure tropical vegetables the number of general feeders is very small. So be knowledgeable about the host plants of your problematic insect pests and alternate from host to non-host as best you can manage.

Crop rotation with non-host crops is an effective method for managing insect pests attacking tomato. The selection of an appropriate non-host crop is challenging, because most of the tomato pests are highly polyphagous and feed on several agricultural and horticultural crops as well as weed plants. Non-solanaceous crop rotation is an effective way to reduce the population buildup of brinjal shoot and fruit borer. However, careful consideration in choosing the crops for rotation is imperative, because the crops selected (e.g., cotton or okra) may also support other common pests e.g., whitefly, leafhopper and aphids. Cotton followed by okra will increase leaf hopper populations and they may harbor the little leaf of eggplant disease. Hence, the identification of suitable and non-host crops is vital role when employing cultural control tactics.

Time of Planting

Variations in time of planting are also important and can result in plants out growing those late arriving pests. Time of year and weather conditions, hot and dry or wet can affect the crops and their insect pests. Inter planting different plant species in some fields can slow down the pest species from locating the crop and establishment. This is especially true for single host pests or those with just a few hosts. Relay plantings should also be avoided in space and time in that such a practice has the advantage of easy movement and quick establishment of all pests.

Trap Cropping

Growing of preferred or susceptible plants of important pest species (trap crop) near a major vegetable crop and subsequently destroying it or killing it with insecticides is an effective control tactic. Further, if the trap crop is flowering the nectar may serve as a food for natural enemies (predators or parasitoids) and therefore enhance the natural control of insect pests.

Growing castor as a trap crop, on the borders of vegetable fields (onion, chillies, etc.) reduces *S. litura* infestations. The castor should be sown 1 month prior to transplanting. Inter cropping of a one row of a tall variety of marigold after every 16 rows of tomato acts as a trap crop. It helps to reduce the incidence of tomato fruit borer and root knot infestation. The 40 days and 25 days old marigold and tomato planting of seedlings respectively is ideal for the control of insect pests in tomato (Fig. 5.3).

Two rows of mustard between every 25 rows of brassica, is an effective way for reducing the diamond-back moth populations and their damage. One row of mus-

Fig. 5.3 Intercropping tomato with marigold

tard should be sown 15 days before the brassica planting, and a second sowing is recommended on the adjacent ridge on the 25th day after planting brassica (Srinivasan and Krishnamoorthy 1992).

Transfer of Pest Management Technology to Vegetable Farmers

Dissemination of pest information and pest control strategies to end users, in a timely manner, is the responsibility of university researchers and extension service, pest control industry, government extension agencies, local pesticide dealers, trained local farm advisors, field consultants and NGO professionals (Rabb and Guthrie 1970; Ross 1967; (Fig. 5.4). In the United States the Land Grant Universities in each state conduct research and translate the findings into specific control recomendations for the farmer, home owner, governmental and private agencies, field consultants and farm advisors. Traditionally, local country extension agents address the local geographical information for practical adoption of pest control methods and effective use. Much effort and support has been directed to “train the trainer” programs by donors (foundations, organizations, and NGOs) Ministries of Agriculture. This technical information is based on detailed knowledge of local professionals on the insect pests, their life history, and the latest control methods developed. They may identify the pest, do some insect monitoring and even some surveying and forecasting of pest populations. They conduct pest control demonstrations on farms and follow up with field days and even provide specific recommendations of specific control methods to choose and to use. Hard copy publications and more recently online or electronic information are used to place requested and useful information in the hands of the farmers or advisors. This approach is a life-long professional endeavor to extend the latest findings and to help in the safe and economical production of a constant and sustainable food supply for all consumers.

Fig. 5.4 (**a**), (**b**), (**c**), Technology transfer to vegetable farmers

Fig. 5.4 (continued)

Conclusion

Selection and use of methods of insect pest control, or management, is based on the following considerations. The use of one control method over another depends on many factors. Among these are the following: economics, cost comparisons between all control methods, technical difficulties, availability, dependence on chemicals, lack of efficacy, need for more research, impractical for one or more reasons, and lack of specific targeting and timing. Other considerations include these statements: Is the need in pre-harvest, time of harvest or postharvest situations? Is the crop of high or low value? Is the use in developed or developing countries where labor is available and shipping to distant or close markets is possible? Is the market fresh or processed, near or distant? Obviously economics in costs verses benefits, cost relative to technologies that exist, the dependence on chemical insecticides, and the availability of technologies must be considered (Novartis 1997; Oseto 2000; Panneton et al. 2001a, b; Vincent et al. 2001, 2003). Targeting is a major challenge in developing physical and cultural control methods for field use (Sorensen 1972–82, 1978–80a, b, 1987, 1996, 2002, 2005b). Likewise, is the difficulty with insecticide sprays, where less than 0.03 % of the foliar spray against aphids on field beans is effectively used for killing the insect pests (Matthews 1992).

As we move to developed countries legal, environmental and safety regulations may restrict the use of certain practices and particularly pesticides. Competition for markets within and between countries affects the methods used or required. In postharvest vegetables there is zero tolerance for pest damage and pest presence. Hence, physical, mechanical and cultural, control is often applied early as a preventative and throughout the growing period along with timely applications directed at targeted pests with selective and effective safe insecticides.

Advances in computer technologies (expert and GPS Systems), the increased use of weather balloons and drones, weather and pest forecasting, the availability of digital and internet sources have provided a great deal of technical and timely information on insect pests, their biology, control and management at everyone's fingertips. Insect modeling and application in the field along with computer capabilities and high-speed sensor technologies have helped to target pests with the effective use and selection of any and all methods of pest control (Panneton et al. 2001a, b; Terry et al. 1983; Vincent and Chagnon 2000; Vincent et al. 2003).

A constant concern is the widening technological and economic gaps between developed and developing countries (Oseto 2000; Panneton et al. 2001a, b) With different agronomical, horticultural and entomological problems under temperate and tropical conditions, there still exists a need to adopt effective IPM programs including physical and cultural practices and even genetically engineered plants (GMO) in pest control strategies (Novartis 1997; Rabb and Guthrie 1970). Food production and human health standards can help to meet the growing demands of global markets through exchanging technology with those in temperate and tropical countries, in both developed and developing countries, as the world grows smaller and communication and resources are shared. Technical solutions to manage insects can be applied in all socioeconomic, ecological and political realities over the period of time (Novartis 1997; Rabb and Guthrie 1970; Ross 1967; Sorensen 2008, 2009; Vincent et al. 2003).

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Chapter 6
Integrated Pest Management of Cruciferous Vegetables

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Abstract Vegetables are important components for global and nutritional security. Cruciferous crops are one of the important contributors to total vegetable production and are most commonly consumed as green and cooked vegetables worldwide. They are attacked by wide array of insect pests and diseases which significantly reduce their quality and yield. In this chapter, the bioecology of economically important pests and diseases and the IPM packages developed globally to manage them are discussed.

Keywords Crucifers • Insect pests • Diseases • IPM • Food security

Introduction

Cruciferous crops are one of the important contributors to total vegetable production and the most abundantly consumed vegetable (Shaila 2007). The commercially important cruciferous crops are cabbage, cauliflower, broccoli, and Brussels sprouts.

Among, the cruciferous crops grown in India, cauliflower ranks first in area (433,900 ha), and second in production (8,573,300 t) and productivity (19.8 t/ha) (Singh and Jyoti Devi 2015). Cabbage is cultivated in an area of 400,100 ha with the production and productivity of 9,039,200 t and 22.6 t/ha respectively (Indian Horticulture Database 2014). Cruciferous crops are extensively grown throughout the year except for winter months in the temperate and summer months in the

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Table 6.1 Yield loss due to major insect pests

Insect pest	Yield loss (%)
Diamondback moth, *Plutella xylostella*	17–99
Cabbage butterfly, *Pieris brassicae*	69–71
Cabbage borer, *Hellula undalis*	30–58
Cabbage leaf webber, *Crocidolomia binotalis*	28–51
White rust	30–60
Club root	75–80
Black rot on cabbage and cauliflower	50
Fusariam wilt of radish	20–40

tropical regions. They are attacked by wide range of insect pests and diseases which significantly reduce their yield and quality. In India alone, about 37 insect pests have been reported to feed on cabbage (Lal 1975; Loganathan 2002; Devjani and Singh 2002).

Important Pests of Cruciferous Crops

The occurrence and severity of insect pests on cruciferous crops vary with host, location and season. Though different pests attack crucifer crops, their damage varies based on their abundance, climatic conditions, host plants and management practices. The yield losses caused by the major pests of crucifers are listed in Table 6.1 (Bernier 1972; Anuradha 1997; Shivalingaswamy et al. 2002; Mangili et al. 2003; Rekha et al. 2011; Rai et al. 2014; Singh 2015).

Since, crucifers are a highly remunerative vegetable crop, farmers adopt intensive plant protection measures that involve use of insecticides and result in environmental and health hazards and resurgence of pests and diseases.

Insect Pests of Cruciferous Vegetables

Diamond Back Moth (DBM) *Plutella xylostella* (Plutellidae: Lepidoptera)

It is considered the most important pest of cabbage, hampering its production (Philips et al. 2014) and is known to feed mostly on cruciferous plants (Talekar and Shelton 1993).

All plant growth stages are susceptible to attack by DBM. The early instar larvae feed on the under-surface of the leaves without damaging the upper epidermis and cause windows in the leaf (Webb 2013). Later stages of larvae make holes in leaves. The moth is grayish brown with narrow wings having pale white markings anteriorly which form diamond-like white patches dorsally when the wings are folded over the back at rest (Webb 2013). It lays up to 57 eggs mostly on the under surface of leaves along the veins either singly or in groups. Oviposition period is 4–5 days (Navarajan Paul 2007). The larvae are greenish and larval duration duration ranges from 13 to 21 days. Pupation occurs in a thin silken cocoon attached to the leaves and the pupal period ranges 7–14 days (Navarajan Paul 2007; Webb 2013). The total life cycle from egg to adult range 24–35 days (Navarajan Paul 2007).

Cabbage Butterflies, *Pieris brassicae* and *P. rapae* (Lepidoptera: Pieridae)

In India, these butterflies are distributed along the entire Himalayan region. They pass winter in the plains and migrate to hilly regions during summer (Atwal and Dhaliwal 2008). On hatching, the young caterpillars feed by scraping the leaves and later feed gregariously on leaves making irregular holes (Atwal and Dhaliwal 2008). Feeding results in the skeletonization of leaves and holes bored in the heads of cabbage and cauliflower (Navarajan Paul 2007). Female moths lay conical-shaped, yellow colored eggs, either singly or in groups, on the undersides of leaves and the fecundity ranges from 160 to 200. The egg stages lasts 3–17 days. Larval period ranges 15–45 days. Pupation takes place on host plants or nearby plants and debris. Pupal duration is 7–28 days. Adult butterflies have snow-white forewings with black distal margins and hind wings are white (Webb 2013).

Cabbage Cluster Caterpillar, *Crocidolomia pavanona* (Lepidoptera: Pyralidae)

Eggs are flat and laid in overlapping masses containing 40–100. The larvae remain on the under surface of leaves in webs and skeletonize them by feeding (Navarajan Paul 2007). The incubation period ranges from 5 to 15 days depending on the weather. The larva has a red head and brown longitudinal stripes and rows of tubercles, with short hairs, on its pale violaceous body. It attains the pupal stage within 24–27 days during summer and in 51 days during winter. Pupation occurs in an earthen cocoon and the adult emerges in 14–20 days (Sudarwohadi and Setiawati 1990).

Cabbage Borer, *Helula undalis* (Lepidoptera: Pyralidae)

The larvae, loosely enclosed in a web, feed on young leaves and bore inside the growing tip (Mewis et al. 2001). Each female moth lays an average of 27 eggs per day and up to 175 eggs in its life time (Sivapragasam and Aziz 1990). Eggs laid singly or in clusters of 4 or 5 on the lower surface of leaves and near buds hatch in 3–4 days. The larval stage ranges from 10 to 15 days (Messing and Mau 2007; Singh and Rose 2009).

Cabbage Looper, *Trichoplusia ni* (Lepidoptera: Noctuidae)

It is a polyphagous pest. Adult moths have brown, mottled fore wings with two small silver spots at the center. Small, round, greenish white with longitudinal corrugations, are either laid singly or in small clusters on the plant. Eggs hatch in 3–5 days and the fecundity ranges from 300 to 600 eggs/moth. Young larvae damage plants by chewing holes in the leaves and on reaching maturity have caused severe defoliation and plant damage. Larvae are green colored with white stripes running the length of their bodies. Larvae pupate on the lower leaf surface or in plant debris within a thin cocoon. The pupal period duration is 10–14 days (Webb 2013). The total life cycle is about 30–35 days.

Cutworms, *Spodoptera litura* and *Agrotis* spp. (Lepidoptera: Noctuidae)

Cutworm larvae cause plant damage by eating the foliage of young plants and by feeding on the heads. Cutworm larvae may damage some of the lower leaves where these touch the ground. Cutworms feed at night and during the day hide in the crop debris next to the damaged plant. The larvae which may reach a length of up to 40 mm, are usually a greasy grey to dark brown or almost black in color, with several black tubercles on each segment. The nocturnal moth has brown or greyish forewings and light brown hindwings (Webb 2013).

Aphids, *Myzus persicae* (Sulzer), *Brevicoryne brassicae* and *Lipaphis erysimi* (Hemiptera: Aphididae)

Aphids feeding in colonies cause damage by sucking the sap on the undersides of the leaves and tender shoots resulting in stunted growth and malformation of the plant. During severe infestation plants may completely dry up. Due to honey dew exudation, sooty mold growth developing on plant parts ultimately hinders the photosynthesis and adversely affects plant growth. Cloudy weather conditions favor the spread of their infestation (Webb 2013). Reproduction in aphids is mostly by parthenogenetic vivipary and a single female may produce 40–45 nymphs. Sexual reproduction has been reported during severe winters (Navarajan Paul 2007). Eggs are pale yellow with a greenish tinge. Nymphs are yellowish-green while adults are dark colored. The total life cycle is completed in 11–45 days and as many as 21 generations have been recorded during a year under favorable conditions.

Whitefly, *Bemisia tabaci* (Hemiptera: Aleyrodidae)

Nymphs and adults suck the sap, usually from the under surface of the leaves, and excrete honeydew. Affected leaves curl and dry and the plants show a stunted growth.

Painted Bugs, *Bagrada cruciferarum*, *B. picta* and *B. hilaris* (Hemiptera: Pentatomidae)

Both nymphs and adults suck cell sap from tender plant parts causing yellowing of leaves which gradually dry, and ultimately drop, exposing the plants to secondary invasion of bacteria and fungi. Heavy infestation can seriously reduce growth and yields. They feed on plants immediately after emergence of the hypocotyl (Palumbo and Natwick 2010) and cause damage up to 60 %. *B. hilaris* prefer mainly the wild and cultivated mustards.

Female bugs lay pale yellow colored oval shaped eggs either singly or in batches on leaves, stems and flower buds. A single female may lay up to 100–200 eggs (Hill 1983). The eggs hatch in to nymphs within 2–5 days. Nymphs are patterned with a mixture of black, white and orange color. Total nymphal period is 18–20 days (Reed et al. 2013). The life cycle is completed within 3–4 weeks.

Crucifer Flea Beetles, *Phyllotreta* spp. and *Chaetocnema basalis* (Coleoptera: Chrysomelidae)

The small adult beetles mostly attack the cotyledons, make numerous shot holes and cause leaf necrosis. Damage to the growing point of the seedlings causes plant death. Long, warm, sunny and dry conditions favor their feeding (Knodel and Olson 2002; Anon. 2002). Adult beetles are metallic bluish green in color and fecundity ranges from 50 to 80 eggs/female. The grubs emerge within 5–10 days and the grub period is about 9–15 days. Pupation takes place in soil and the pupal period is 10–18 days.

Red Spider Mite, *Tetranychus urticae* Koch (Acari: Tetranychidae)

These reddish-brown mites suck sap from the underside of leaves and tender young heads of broccoli and cauliflower. The feeding punctures result in the formation of white specks followed by yellowing, bronzing and drying of affected plant parts. They weave a fine web on leaf surfaces.

Major Diseases of Cruciferous Vegetables

Club Root, *Plasmodiophora brassicae*

This pathogen is known to occur worldwide on all crucifers. Infected roots serve as the major source of inoculum and release zoospores which infect root tissue. Young plants affected by this disease often die whereas older plants are unable to produce a marketable product (Conn and Rosenberger 2013). The other symptoms are yellowing, stunting and wilting of plants. Low lying, poorly drained soils with a soil temperature of 15–25 °C and acidic soil conditions highly favor disease incidence (Conn and Rosenberger 2013). The pathogen will spread through farm implements, irrigation water, and infected seedlings (Prakasam 2005). Due to its long persistence (10 years or more) in soil, the fungus is not readily controlled by crop rotation (Wukasch and Hunter 1985).

Damping-Off, *Pythium* spp.

Pythium is a soil borne disease. Initially, water soaked lesions develop near the collar region of the stem and later become brown lesions. This ultimately leads to girdling at the infected portion and toppling and drying of plants (Chandrasekar 2012; Conn and Rosenberger 2013).

White Rust, *Albugo candida*

Albugo candida is an obligate biotrophic fungus and its damage varies from host to host. The fungus has a wide host range including more than 400 plant species belonging to 31 families. The most preferred host plants are horseradish, field mustard, Indian mustard, brown mustard, rutabaga, cauliflower, broccoli, cabbages and radish.

The disease is identified by the presence of white blisters on the undersides of infected leaves (Armstrong 2007). Initially, the infected host plants show chlorosis followed by necrosis, defoliation, swelling, distortion of stems and flowers, stunted growth, and leaf curling (Babadoost 1990), a condition referred to as 'stagheads' (Armstrong 2007).

Downy Mildew, *Hyaloperonospora parasitica (Peronospora parasitica)*

The symptoms are yellow, purple or brown irregular shaped areas on upper leaf surfaces, which also produce white to gray, downy fungal spore masses on abaxial leaf surfaces (Chandrasekar 2012). Under heavy incidence, sporangia develop on the upper leaf surface, which leads to death of seedlings. Heavy fog, light rains, prolonged leaf wetness and night temperatures of 8–16 °C generally favor disease development.

Phytophthora Root Rot, *Phytophthora megasperma*

Many cruciferous crops and weeds are attacked. Discolored, red or purple, leaf margins, from the tips and spreading to the stem, result in leaf dieback and ultimately wilting and drying of plants (Prakasam 2005). Wet, poorly drained soils and temperatures between 13 and 25 °C generally favor this disease (Conn and Rosenberger 2013).

Powdery Mildew, *Erysiphe cruciferarum*

Symptoms begin as white lesions on the upper surface of the foliage and later they gradually coalesce and appear as a white powdery growth. Infection is highest on cabbage and cauliflower and the disease reduces head and curd size respectively (Conn and Rosenberger 2013). Many weeds serve as alternate hosts in the off-season. Water stress of the host also favors infection (Prakasam 2005).

Cercospora Leaf Spot, *Cercospora brassicicola*

Circular or angular brown spots with a pale green to whitish center appear on leaves followed by chlorosis. Severely affected plants are defoliated (Prakasam 2005).

Alternaria Leaf Spot, *Alternaria brassicae, A. brassicicola* and *A. raphani*

Symptoms begin as small, circular lesions and develop as concentric rings with chlorotic spots which may break giving a shot hole appearance to the leaf which is covered with a sooty mold growth (Prakasam 2005; Sardana and Sabir 2007). In cauliflower and broccoli, it causes browning and reddening of heads respectively (Conn and Rosenberger 2013). The seed borne conidia are generally disseminated by wind and water.

Black Leg, *Leptosphaeria maculans* (Anamorph: *Phoma lingam*)

Oval, sunken, light-brown cankers appear near the base of stems and later enlarge and girdle the stems. Under favorable conditions, small black fruiting structures (pycnidia) develop in stem cankers and leaf spots. Severely infected plants are stunted and wilt.

Ring Spot, *Mycosphaerella brassicicola* (Anamorph: *Astromella brassicae*)

Initially, water-soaked lesions appear and expand to form concentric yellow rings giving a tattered appearance on leaves and stems (Conn and Rosenberger 2013).

Bottom Rot, *Rhizoctonia solani*

Symptoms appear as brown lesions and later wilting and senescence of plants takes place (Conn and Rosenberger 2013).

Black Root, *Aphanomyces raphani*

Bluish-gray to black lesions develop on roots and infected tissue remains firm (Prakasam 2005). Warm temperatures of 20–27 °C and RH of 68–80 % favor infection and subsequent disease development (Conn and Rosenberger 2013).

Verticillium Wilt

Common hosts are cauliflower and Chinese cabbage. V-shaped lesions with yellow borders develop along margins of lower leaves. Vascular tissue develops a dark brown discoloration, which can extend from the roots into the stem. Continuous soil moistness favor disease incidence (Conn and Rosenberger 2013).

Black Rot *Xanthomonas campestris* pv. *campestris*

First symptoms are yellow 'V' shaped patches, followed by dropping of lower leaves, blackening of leaves, stem and roots and pre-mature plant death (Sardana and Sabir 2007). The bacteria mostly enter through the hydathodes of leaf margins and insect wounds and further spread via rain splashes, leaf veins and mechanical injuries (Anon. 1999). The disease is usually prevalent in low areas and where plants remain wet for long periods. Under these conditions crop loss may exceed 50 % due to the rapid spread of the disease (Anon. 1999). The optimum temperature for infection is 27–30 °C (Sardana and Sabir 2007; Conn and Rosenberger 2013).

Bacterial Leaf Spot, *Pseudomonas syringae* pv. *maculicola*

Common hosts are cauliflower, broccoli, cabbage, Brussels sprouts and turnips. Initially, water soaked lesions develop on leaves and become dark brown or purple with puckering and a ragged appearance. On cauliflower this disease is characterized by the presence of peppery spots. It is a seed borne disease and spreads through rain splash or irrigation water. Incidence is highest during cool and wet weather periods (Anon. 1999; Prakasam 2005).

Bacterial Soft Rot, *Pseudomonas marginalis* pv. *marginalis*

Symptoms first appear on leaves as small, water-soaked lesions and quickly enlarge to produce soft, mushy tissues having a foul odor. The bacteria survive in soil and decaying plant material and spread through water, rain and maggots of several species of flies enter the plants through wounds. It also acts as pre-disposing factor for *Erwinia* spp. and *Pseudomonas* spp. (Conn and Rosenberger 2013).

Soft Rot, *Sclerotinia sclerotiorum*

It commonly occurs on cabbage, cauliflower, broccoli and common ragweed (*Ambrosia artemisiifolia*). White, cottony growth and black sclerotia appear on infected plant tissues. Bacterial development is generally favored by abundant soil moisture (Prakasam 2005; Conn and Rosenberger 2013).

Cauliflower Mosaic: *Cauliflower Mosaic Virus (CaMV)*

This disease is transmitted by the cabbage aphid (*Brevicoryne brassicae*, false cabbage aphid (*Lipaphis erysimi*) and green peach aphid (*Myzus persicae*) (Agrios 2005). It is mostly prevalent in United States and Europe and attacks all crucifers. Symptoms include chlorosis along leaf veins (vein clearing) at the leaf base, dark green bands in remaining areas, and necrosis and stunting of plants. Chinese cabbage is highly susceptible to CaMV.

Radish Mosaic: *Radish Mosaic Virus (RaMV)*

It is transmitted by leaf beetles (Agrios 2005). The disease is most serious in Japan, Europe and the U.S.A. Common symptoms include mosaic, ring spots, leaf distortion, veinal necrosis, and leaf enations. In cauliflower and cabbage, symptoms appear as chlorotic and necrotic lesions along with a mosaic pattern.

Turnip Mosaic: *Turnip Mosaic Virus (TuMV)*

It is generally transmitted via mechanical means and aphid feeding (Agrios 2005). Major hosts are cabbage, turnip, cauliflower, radish and broccoli. Initially circular, light green lesions, develop on the abaxial leaf surface. Later, they coalesce, resulting in large necrotic spots and defoliation. The ideal condition for disease development is between 20 and 28 °C.

Turnip Yellow Mosaic: *Turnip Yellow Mosaic Virus (TYMV)*

It is transmitted by flea beetles, mustard beetles, grasshoppers and earwigs (Agrios 2005). This virus only infects crucifers, especially cabbage, cauliflower and turnip. It is most prevalent in Western Europe on cauliflower and causes vein clearing followed by permanent leaf yellowing.

Turnip Yellows Virus (TuYV)

Its common hosts include *Beta vulgaris*, *Lactuca sativa*, *Spinacia oleracea*, and *Raphanus sativus*. It is transmitted by *Aphis craccivora*, *A. gossypii*, *Acyrthosiphon solani*, *Brachycaudus helichrysi*, *Brevicoryne brassicae*, *Macrosiphum euphorbiae*, *Myzus ascalonicus*, *M. ornatus*, *M. persicae*, and *M. humuli* (Brunt et al. 1996). Symptoms appear as mild chlorotic spots followed by yellowing, thickening and brittleness of older leaves.

Important Nematode Pests of Cruciferous Crops

Cyst Nematode, *Heterodera cruciferae* (Heteroderidae)

The major host plants are cabbage and cauliflower. It is a sedentary endo-parasitic nematode. Initial symptoms are similar to nutrient deficiency. As the disease progresses plants wilt, especially during the hot weather period. Invaded roots produce profuse branches, while the taproot remains small and produces loose, small heads/curds, discolored roots and ultimately causes plant death. The important characteristic feature of this nematode is production of lemon-shaped, tanned, white, hard cysts on the root surface (Conn and Rosenberger 2013). These nematodes overwinter as cysts and after hatching release the juveniles that penetrate host root tissues (Jonathan et al. 2005).

Root Knot Nematode, *Meloidogyne* spp. (Meloidogynidae)

It is a polyphagous pest. It exhibits a sedentary endoparasitic habitat on host plants. Symptoms are similar to club root disease, but vary in terms of producing small sized, discontinuous tough root knots (swellings) on roots and rootlets. They cause prolific root branching and produce galls above the point of infection. This condition also acts as a pre-disposing factor for the secondary infection by many fungi and bacteria. Apart from this, it also produces stunting, chlorosis and wilting of plants. Though infected plants may survive a growing season, the resulting crop is generally small (Conn and Rosenberger 2013). Sandy soil with a moderate level of moisture favors the infection of *M. incognita*. Maximum infection occurs at soil temperatures of 10–35 °C (Jonathan et al. 2005). Among crucifers, cabbage is the least preferred host to root knot nematode (Bafokuzara 1983; Carneiro et al. 2000; Manfort et al. 2007).

Reniform Nematode, *Rotylenchulus reniformis* (Hoplolaimdae)

It is a sedentary, semi-endoparasite that damages beans, cabbage, carrot, cauliflower, cucumber, eggplant, peas, cowpea, radish, okra and lettuce. The pre-adult females and second stage juveniles are parasitic and initiate infection by destroying the root epidermis and cause necrosis and disintegration of phloem cells in the stellar region of plants (Mwangi et al. 2014). Adult females are reniform-shaped and, they insert their head and neck inside the roots whereas the posterior reniform shaped body remains outside the root. The female lays 150–200 eggs in gelatinous matrix (Jonathan et al. 2005).

Integrated Pest Management Practices

The IPM Innovation Lab working in Asia for two decades has developed a generalized IPM package for cruciferous crops in tropical Asia. Since IPM is specific to crop, season and locality, this package requires adjustments to meet the local conditions. It primarily aims at minimizing the use of synthetic chemical pesticides and recommends their use when necessary with caution.

The components of an IPM package for cruciferous crops are:

1. Selection of healthy, disease free, climatically adopted and high yielding seeds.
2. Using resistant varieties for arthropod pests and diseases.
3. Solarization of seed beds, if possible.
4. Raising seedlings in plastic trays and using sterile media like coco-peat.

5. Covering seed beds/seedling trays with nylon netting to prevent insect infestation.
6. Treating seeds/seedlings with *Trichoderma* spp. *Pseudomonas fluorescens*, and *Bacillus subtilis*.
7. Treating seedbeds/nursery floor with *Beauveria bassiana* to kill nymphs of thrips that reach floor for pupation.
8. Treating the field with neem cake to control nematodes.
9. Crop rotation with non-cruciferous crops, especially with cereals.
10. Trap cropping.
11. Field sanitation – removal of residual crop material immediately after harvesting.
12. Intercroppping.
13. Use of reflective mulches for repelling insect pests.
14. Use of pheromone traps.
15. Augmentative release of natural enemies.
16. Use of botanical pesticides
17. Use of microbial pesticides like, *Bacillus thurigiensis*, *Beauveria bassiana*, *Metarhizium anisopliae*, NPVs and others.
18. Need based use of selective pesticides.

Selection of healthy and disease-free seeds for planting to prevent occurrence of these seed-borne diseases in the later stages of the crop.

Resistant varieties Early Patna, EMS-3, KW-5, KW-8 and Kathmandu local are resistant cabbage varieties against *H. undalis*. Similarly, All season, Red drum head, Sure head, Express mail are some of the promising resistant varieties grown in India against cabbage aphid (Rai 2012). Cabbage varieties such as Atlantis, Blue Dynasty, Bronco, Cecile and Ramada and broccoli varieties viz., Arcadia, Eureka and Greenbelt are reported as resistant to black rot disease (Seebold et al. 2008).

Soil solarization of seedbeds with thick polythene sheets (eight gauge) to maintain the heat up to 45 °C controls nematodes and fungal diseases (Jonathan et al. 2005; Ramakrishnan 2012). Hot water seed treatment of cabbage and cauliflower @ 50 °C for 30 min kills the downy mildew fungi (Singh and Jyoti Devi 2015) and bacteria causing black rot (Anon. 1999; Chandrasekar 2012).

Clean cultivation, crop rotation, removal of alternate weed hosts and crop residue immediately after last harvest, and adequate fertilization are recommended to reduce occurrence of insect pests and diseases caused by fungi, bacteria and viruses (Conn and Rosenberger 2013).

Seed treatment with *Trichoderma viride* @ 4 g/kg or *Pseudomanas fluorescens* @ 10 g/kg of seeds (Sardana and Sabir 2007) controlled the growth of *Pythium* and *Phytophthora* fungi. Treating seedlings with *Trichoderma* spp. and *Bacillus subtilis* induces defence in the plants. Treatment with *P. fluorescens* reduces nematode damage.

Intercropping with tomato, garlic, clover coriander, marigold, lucerne, onion and spearmint in cabbage fields acted as a repellent to *P. xylostella* (Talekar et al. 1986; Facknath et al. 1986, 1999; Timbilla and Nyako 2001; Uma Shankar et al. 2007).

Indian mustard was the preferred host for oviposition by *P. xylostella* and *C. pavanona*. Muniappan and Lali (2000) reported preferred plants for ovipoisiton were radish variety Minowase 3 for *H. undalis*, Chinese cabbage variety Tempest and Indian mustard for *C. pavonana*, Indian mustard for *P. xylostella* and recommended using them as trap crops in the cabbage fields. Growing of crucifers with high leaf wax and trichome density reported to have resistance to *P. xylostella* (Agerbirk et al. 2003; Handley et al. 2005).

Release of the egg parasitoid, *Trichogramma chilonis*, @ 50,000/release/ha at weekly intervals from flowering at four to five times and the larval parasitoid, *Cotesia plutellae*, @ 50,000/release/ha at 50 days after transplanting, and spraying of *Bt* formulations to give good larval control of DBM, cabbage borer and the leaf webber (Navarajan Paul 2007; Singh and Jyoti Devi 2015). Release of the first instar grub of *C. zastrowi arabica* @ 50,000/release/ha is a good bioagent against cabbage aphid (Satpathay et al. 2005). Similarly, *Bt* @ 0.7 mL/lit is effective to *C. pavanona* (Gopalkrishnan and Vishalakshi 2001). Spraying of SlNPV @ 250 LE/ha + jaggery (1 kg) + sandovit (100 mL) or robin blue (50 g) thrice at 10 day intervals (Rai 2012) is effective on *S. litura* and cutworms.

Pheromone traps for *H. armigera*, *S. litura*, and *P. xylostella* should be installed. Yellow sticky traps should be installed for aphids and whiteflies. Installation yellow sticky traps and mulching with reflective sheetswill reduce the incidence of aphids and aphid transmitted viral diseases.

Neem formulations are effective in controlling lepidopteran, hemipteran and acarine pests and fungal and bacterial diseases. Bio-pesticides *Beauveria bassiana*, *Metarhizium anisopliae*, *Bacillus thuringiensis* and NPVs on specific pests of cruciferous crops.

Conclusion

Despite the significant achievements in production of cruciferous crops, serious challenges from many pest and diseases continue. As discussed, farmers mainly rely on the use of synthetic pesticides for the management of the majority of biotic stresses. Massive applications of pesticides increase the problems such as insect/pathogen resistance, environmental degradation, high input costs and human poisoning. Development of IPM with the inclusion of newer green labeled pesticides would minimize losses from the various pests and be compatible with ecological sustainability. Hence, ecosystem-based management strategies help to focus on long-term prevention of pests in crucifer crops through the utilization of all available IPM techniques.

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Chapter 7
Integrated Pest Management of Okra in India

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Abstract Okra (*Abelmoschus esculentus* (Malavaceae), a major contributor to global vegetable production, is an excellent resource for overcoming global malnutrition and rural poverty. Globally, okra is cultivated on an area of 1.12 mha with a production and productivity of 8.71 mt and 7.8 t/ha respectively. Pests and diseases are major constraints to the quality and quantity of okra produced with total losses of about 35–40 %. Farmers rely on the use of synthetic pesticides for the control of pests thereby endangering environmental and public health. In this context, this chapter describes the biology and etiology of the key pests and diseases of okra and describes the development of components that are integrated into a package of practices as alternatives to the use of pesticides. The Integrated Pest Management (IPM) approach termed the “okra IPM package” registered significantly lower populations of aphids, whiteflies, leafhoppers, leaf miners, nematodes, fruit borer damage and incidence of *Yellow vein mosaic virus* and powdery mildew coupled with an increase in shoot and root growth and natural enemy populations as compared to the farmer’s practice which consisted of the use of conventional pesticides. The yield increase in the IPM plots was 12.43–45.54 % above the farmers practice. The benefit:cost ratio was 2.53–3.23:1 in the IPM plots as compared to 1.23–1.52 in the farmer’s practices plots. In addition, the IPM approach was environmentally safe and provided residue-free produce for the consumers.

Keywords Insect pests • Mites • Nematodes • Fungal and viral diseases • IPM package for okra

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Introduction

Vegetables are one of the best resources for overcoming malnutrition problems and provide considerable revenue to farmers in a short time span. Okra (*Abelmoschus esculentus* (Malavaceae), one of the important malvaceous vegetables also called as bhendi or lady's finger in India, is a major contributor to the total global vegetable production. It is believed to have originated from Ethiopia (Joshi and Hardas 1976). It is one of the important vegetable crops grown extensively in the tropical, subtropical and warm temperate zones of the world (Charrier 1984; Thompson and Kelley 1957). Okra is grown commercially in India, Turkey, Iran, Western Africa, Yugoslavia, Bangladesh, Afghanistan, Pakistan, Burma, Japan, Malaysia, Brazil, Ghana, Ethiopia and the Southern United States (Anon. 2010) and warmer parts of Temperate Asia, Southern Europe and Northern Africa (Oyelade et al. 2003). Globally it is cultivated on an area of 1.12 mha with a production and productivity of 8.71 mt and 7.8 t/ha respectively. Okra is an important vegetable crop for Indian agriculture and is grown extensively throughout the year in all parts of the country with an area of 0.53 million hectares, annual production of 6.35 mt and a productivity of 11.9 t/ha (Indian Horticulture 2014). India is ranked first in production of okra and contributes for 73 % of global production and is second in the total okra cultivable area (Singh et al. 2015). The global climate scenario is having a significant impact on vegetable cultivation including okra.

One of the major constraints to the quality and quantity of okra produced is the increasing incidence of insect pests, diseases and nematodes. Due to their tender and supple nature and their cultivation under high moisture and input regimes, okra is susceptible to pest attack yielding total losses of about 35–40 % (Sardana et al. 2006). In India, Rai (2015) reported that the yield loss of okra is due to major pests (Table 7.1) and their incidence on okra varies across the globe.

In many areas in India, okra is grown adjacent to cotton which is another malvaceous crop. Most of the pests that attack cotton also attack okra. The important insect pests include fruit and shoot borer (*Earias vittella* and *E. insulana*), tomato fruit borer (*Helicoverpa armigera*), cotton leaf roller (*Sylepta derogata*), leafhopper (*Amrasca biguttula biguttula*), leafminer (*Liriomyza* spp.) whitefly

Table 7.1 Yield loss due to major pest damage in okra in India (Rai 2015)

Insect pest/disease	Yield loss (%)
Fruit and shoot borer (*Earias vittella*)	23–54
Tomato fruit borer (*Helicoverpa armigera*)	22
Whitefly (*Bemisia tabaci*)	54
Jassids (*Amrasca biguttula biguttula*)	54–66
Bhendi yellow vein mosaic virus	50–90
Leaf curl disease	30–70
Cercospora blight	44

(*Bemisia tabaci*), aphid (*Aphis gossypii*), cotton mealybug (*Phenacoccus solenopsis*), dusky cotton bug (*Oxycarenus hyalinipennis*), red cotton bug (*Dysdercus koenigii*), red spider mite (*Tetranychus urticae*) and root-knot nematode (*Meloidogyne incognita*) (Aziz et al. 2011; Karuppusamy 2012; Kedar et al. 2014). Of these, the *Earias* spp. are the most important (Aziz et al. 2011). The other pests attacking okra are semilooper *Anomis flava* and Bihar hairy caterpillar (*Diacrisia obliqua*) (Azad Thakur et al. 2012). Similarly, the important devastating diseases are *Yellow vein clearing mosaic virus*, *Leaf curl virus*, powdery mildew (*Leveilula taurica*) and leaf spot (Ahmed 2000).

Farmers rely on the use of synthetic pesticides for the control of these pests thereby endangering environmental and public health. In this context, IPM for okra serves well for reducing the usage of toxic pesticides.

Description and Biology of Okra Insect Pests

Fruit and Shoot Borers (Spotted Caterpillars), *Earias vittella* and *E. insulana* (Lepidoptera: Noctuidae)

These are oligophagous pests that also attack cotton, *Hibiscus*, hollyhock and other malvaceous plants (Anon. 2011). Larvae bore into tender terminal shoots at the vegetative stage resulting in withering and drying of shoots and dropping of leaves. At the plant reproductive stage it bores into flower buds, flowers, young fruits and the boreholes are plugged with excreta. The infested fruits are deformed and become unfit for consumption (Anon. 2011).

The adult females oviposit sculptured and sky blue colored eggs individually on leaves, floral buds and on tender fruits (Anon. 2014). The egg period ranges from 3 to 5 days and each female lays up to 400 eggs (Anon. 2011). The emerging small, brown, neonate larvae either bore into the top shoots or fruits. Pupation takes place on the outside of fruit or on the plant or crop debris or on the top layer of soil in an inverted boat shaped cocoon. After 6–10 days the adult emerges. The total life cycle is completed within 3–5 weeks (Justo 2005). The adult moth is yellowish-brown. The fore wings of *E. vittella* are pale white, with a broad wedge shaped horizontal green band in the middle, while in *E. insulana* they are uniformly green. Hind wings are white in both the species (Anon. 2010, 2011).

Tomato Fruit Borer, *Helicoverpa armigera* (Lepidoptera: Noctuidae)

It is a cosmopolitan, polyphagous pest, widely distributed in the tropics and subtropics and attacks several vegetable, fruit and cereal crops (Chandurkar et al. 2005; Rai et al. 2005). Among vegetable hosts, okra is the second most important and the most preferred host crop for feeding and oviposition next to tomato (Rai et al. 2005).

Larvae attack the flower buds and fruits and make circular boreholes inside the fruit. The larvae bore the fruits with their bodies protruding from the fruit (Kedar et al. 2014). External symptoms appear in the form of irregular bore holes, plugged with excreta, on fruits.

Spherical, yellowish eggs are laid singly on tender parts and buds of plants and the egg duration is 2–5 days. A single adult female can lay 300–500 eggs in 4–7 days (Kedar et al. 2014). Among the vegetable hosts, survival of neonates is comparatively less on okra due to the presence of mucilaginous substances that is exuded from the fruits (Latheef and Ortiz 1983). The larval period lasts for 18–25 days. The fully-grown caterpillar pupates in the soil in an earthen cell and emerges in 10–21 days (Anon. 2014). Adult moths are medium sized, olive green to brown colored with V shaped marks on the forewings and a conspicuous black spot in the center. Hind wings are light and dull-colored with a black border.

Jassids, *Amrasca biguttula biguttula* (Hemiptera: Cicadellidae)

Jassids (leafhoppers) primarily attack the crop in the early growth stages. Nymphs and adults suck sap from the under surface of the leaves and inject toxins causing marginal leaf curl, downward leaf cupping and browning of leaves known as 'Hopper Burn'. Ultimately stunting and death of plants take place. Jassid populations are favored by the onset of cloudy weather and adversely affected by heavy rainfall (Fakhri and Jamal 2012).

Adult hoppers lay their eggs singly within leaf veins and on the upper leaf surface and eggs have an incubation period of 4–10 days. The nymphs and adults are wedge shaped, pale green with a black spot on the posterior half of the fore wings and their longevity ranges from 7 to 21 and 35 to 56 days respectively (Fakhri and Jamal 2012).

Whitefly, *Bemisia tabaci* (Hemiptera: Aleyrodidae)

Nymphs and adults suck leaf sap, usually from the under surface, and excrete honeydew resulting in a sooty mold growth on leaves. The infested leaves become wrinkled and show the characteristic browning symptom. Infested plants become stunted and fail to bear fruits (Shivanna et al. 2009). The whiteflies are vectors for the *Bhendi yellow vein mosaic virus* (Fakhri and Jamal 2012).

Cotton Aphid, *Aphis gossypii* (Hemiptera: Aphididae)

It is a polyphagous pest (Ahmed 2000). Both nymphs and adults suck the plant sap mostly from the tender plant parts. Severe infestation results in leaf curling, stunted growth, gradual drying and death of plants. Black sooty mold develops on the leaves. Dry conditions favor an increase in pest population and young plants are more susceptible (Kedar et al. 2014).

Cotton Leaf Roller, *Sylepta derogata* (Lepidoptera: Pyralidae)

The larvae within folded leaves feed from the leaf edge towards the mid-rib. In severe cases, complete defoliation occurs. Female moths lay about 200–300 eggs, singly, on the underside of the leaves. The incubation period is 2–6 days. Larvae are green with spots on the body and pupate within 15–35 days. Pupation, which occurs over a 6–12 day period, occurs either on the plant inside the rolled leaves, or on the plant debris in the soil. The total life cycle is completed in 23–53 days. Adult moths, which live for about a week, are yellowish-white, with black and brown spots on the head and thorax and wings with a series of dark brown wavy lines.

Blister Beetles, *Mylabris pustulata* and *M. phalerata* (Coleoptera: Meloidae)

Only the adult stage is destructive and feeds on floral parts of the plant causing significant yield loss. Each female lays about 100–2000 eggs depending on the quality of the food they ingest. The eggs are usually laid in the soil. Upon hatching, the grub feeds on soil-dwelling insects, including pests, and do not cause any damage to the crop. The grubs have several instars, with two or more different forms of larvae. During later instars, it becomes less active, and then pupates.

Red Spider Mites, *Tetranychus urticae* and *T. telarius* (Acari: Tetranychidae)

The nymphs and adults are red in color. Mite infestation is severe in dry and hot environmental conditions. The nymphs and adults suck the cell sap from under surface of the leaf resulting in whitish grey patches appearing on leaves followed by mottling and bronzing and ultimately defoliation. Lall and Dutta (1959) reported 36.8 to 83.2 per cent loss in okra yield due to spider mites. The egg stage lasts for 3–5 days and the egg is 0.13 mm in diameter, globular and translucent. Each female can lay an average of 90–110 eggs during a lifetime of about 30 days; therefore numbers of mites can increase very rapidly during the summer, or under glass or plastic. The larval/nymph stages last 4–5 days. The larva is pale green and has six legs. The nymphs are pale green with darker markings and have eight legs. The adult female is 0.6 mm long, pale green or greenish-yellow with two darker patches on the body, which is oval with quite long hairs on the dorsal side. The male has a smaller, narrower, more pointed body than the female. The total life cycle takes only 8–12 days.

Root-Knot Nematode, *Meloidogyne* spp.

Okra is highly susceptible to root-knot nematodes, *Meloidogyne* species. The above ground symptoms are similar to those described for root rot and wilt diseases. The infected roots are enlarged and distorted. The root-knot nematode has a wide host range. It has a short life cycle of 6–8 weeks. In susceptible hosts, the nematode population builds up to a maximum, usually, as the crop reaches maturity (Shurtleff and Averre 2000) and in some cases the plants die even before maturity (Singh and Khurma 2007).

Important Okra Diseases

Damping Off (*Pythium* sp., *Rhizoctonia* sp.)

Damping off is caused by a fungus and it usually occurs in small patches at various places in the seedbeds or field. The disease spots often increase from day to day until the seedlings harden. Seedlings are extremely susceptible for about 2 weeks after emergence. Infection before seedling emergence (pre-emergence damping off) results in poor germination which is attributed to poor quality of seeds and results in a poor crop stand. Infection on seedlings (post-emergence damping off) causes death or damping-off of the plants which are small and tender. The roots are first killed and then the plant dies.

Fusarium Wilt (*Fusarium oxysporum* f. sp. *vasinfectum*)

The fungus enters the plants through its roots and is mainly transmitted by infected seeds, contaminated farm equipment or through human movement. Warm temperatures increase the prevalence of the disease. The young infected plants exhibit wilting of cotyledons and seedling leaves. Chlorotic spots then appear on the edges of the cotyledon and it then becomes necrotic. Old plants show symptoms of chlorosis and wilting and eventually, the plants die.

Powdery Mildew (*Erysiphe cichoracearum*)

Powdery mildew is very severe disease on okra. Warm and dry weather followed by cool nights that result in dew formation increase the prevalence of this disease and the fungus over-winters in plant debris and or alternate hosts. The symptoms are characterized as appearance of small white spots that lead to formation of white powdery growth on the upper surface due to coalescence of the spots. Heavily infested leaves show curling and appear scorched. The disease later spreads to the entire plant causing a severe reduction in fruit yield.

Bhendi Yellow Vein Mosaic Virus (BYVMV)

Among the various vegetable diseases, *bhendi yellow vein mosaic virus* is the most severe affecting the quantity and quality of the fruits (Uppal et al. 1940). The virus infects all stages of crop growth. The characteristic symptoms of the disease are a homogenous interwoven network of yellow veins enclosing patches of green tissues in the leaf blade (vein clearing). Additional symptoms include vein swelling, slight downward curling of leaf margins, twisting of petioles, dwarfing and retardation of growth (Capoor and Varma 1950). Serious infection of this virus restricts flowering and fruiting (Anon. 2010). The causative virus is transmitted by the whitefly *Bemisia tabaci*.

Okra Enation Leaf Curl Virus (OELCuV)

The pathogen is transmitted through whiteflies The disease symptoms appear predominantly on the lower surface of the leaf as small, pin head enations and later become warty and rough textured followed by twisting of the main stem and lateral branches along with enations (scaly leaf like structures, differing from leaves in their lack of vascular tissue).

Integrated Management of Okra Pests

The okra IPM package, in all three trials conducted at the Tamil Nadu Agricultural University, registered a significantly lower populations of aphids, whiteflies, leafhoppers, leaf miners, nematodes, fruit borer damage, *Yellow vein mosaic virus* and powdery mildew coupled with an increase in shoot and root growth and natural enemy populations as compared to the farmer's practice. The pest population was significantly lower in the different IPM options tested compared with farmers who used conventional pesticides for the control of insect pests. The IPM components include seed treatment with *Trichoderma viride* (4 g/kg) and *Pseudomonas* (10 g/kg), soil application of *Pseudomonas* (2.5 kg/ha), soil application with neem cake @250 kg/ha, maize as border crop against movement of whiteflies and leafminer, use of yellow sticky traps, pheromone traps for monitoring *Helicoverpa* and *Earias*, *Trichogramma* release after each brood emergence of *Helicoverpa* and *Earias*, application of neem oil formulations (2 %), neem seed kernel extract (5 %) and need-based application of new generation safer pesticides.

The pest population was comparatively low in the neem-based treatment compared with farmer's practices as recorded in previous studies (Praveen and Dhandapani 2001; Shabozoi et al. 2011). The yield increase was 12.43–45.54 % above the farmers' practice in the IPM plots. The benefit: cost ratio was 2.53–3.23:1 as compared to 1.23–1.52 in farmer's practice.

The other practices included in IPM of Okra are:

1. The non synchronized sowing of seeds (Rai and Satpathy 1999; Mandal et al. 2007; Gautam et al. 2013)
2. Growing resistant varieties/ hybrids (Table 7.2)
3. Application of NSKE (5 %) or Azadirachtin (5 %) and need based application of safe insecticides if needed.
4. Seed treatment with *Trichoderma viride*
5. Removal of the alternate hosts
6. Installation of yellow sticky traps for monitoring
7. Roguing YVMV affected plants, if any, from time to time
8. Removal and destruction of borer affected shoots and fruits
9. Sprinkler irrigation to reduce the whitefly population
10. Application of botanical insecticides
11. Inundative release of natural enemies such as *Trichogramma brasiliensis* against *Earias vittella* and *H. armigera* and *Chrysoperla zastrowi sillemi* for sap feeders

Table 7.2 Disease tolerant okra varieties in India

Character	Open pollinated varieties	Hybrid varieties
Resistance to *A. gossypii*	Pusa A-4 and Gujarat Anand – Okra-5	–
Resistance to *Amrasca biguttula biguttula*	IC-7194, IC-13999, New selection, Punjab padmini	–
Yellow vein clearing mosaic tolerance	Kashi satdhari, Shitla lila, Parbhani kranti, Arka Abhey, Arka anamika, Varsha uphar, Hissar unnat, Hisar Naveen, Pusa A-4, Punjab-8	Shitla jyoti, Makhmali, tulsi, Anupama-1 and Sun-40
Leaf curl tolerance	Kashi Mohini	Shitla Uphar
Yellow vein clearing mosaic and leaf curl tolerance	Kashi vibhuti, Kashi pragati, Kashi kranti, Punjab padmini and CO(O)- 2 and 3	Lam hybrid selection-1, HBH-142, SOH-152 and Makhmali

Sardana et al. (2006), Anon. (2014), and Rai (2015)

12. Application of bio-agents such as *Bacillus thuringiensis* var. *kurstaki*, HaNPV and entomopathogenic nematode, *Steinernema feltiae* against lepidopteran pests
13. Installation of sex pheromone traps to attract the adult males of *H. armigera* and *E. vittella*
14. Encouraging predators e.g. anthocorid bugs (*Orius* spp.), mirid bugs, syrphid/ hover flies, green lacewings (*Mallada basalis*), predatory mites (*Amblyseius* spp.) and predatory coccinellids (*Stethorus punctillum*) against red spider mites
15. Application of wettable sulphur (0.2 %) to control powdery mildew and spider mites.
16. *Cercospora* leaf spot control by spraying with copper oxychloride

The impact of IPM on okra pests including insects, diseases and nematodes is listed in Table 7.3.

Table 7.3 Impact of IPM on pests (insects, diseases and nematodes) and natural enemies

<table>
<tr><th rowspan="2">Details of observations</th><th colspan="2">Experiment 1</th><th colspan="2">Experiment 2</th><th colspan="2">Experiment 3</th></tr>
<tr><th colspan="2">% reduction over farmer's practice</th><th colspan="2">% reduction over farmer's practice</th><th colspan="2">%reduction over farmer's practice</th></tr>
<tr><td>Aphid population (% leaf damage)</td><td colspan="2">54.0</td><td colspan="2">62.8</td><td colspan="2">66.7</td></tr>
<tr><td>Whitefly population (number per leaf)</td><td colspan="2">70.8</td><td colspan="2">93.3</td><td colspan="2">75.8</td></tr>
<tr><td>Leafhopper population (number per leaf)</td><td colspan="2">64.2</td><td colspan="2">–</td><td colspan="2">65.8</td></tr>
<tr><td>Serpentine leaf minor damage (% leaf damage)</td><td colspan="2">45.3</td><td colspan="2">52.6</td><td colspan="2">59.2</td></tr>
<tr><td>Fruit borer damage (% damage in fruits)</td><td colspan="2">62.8</td><td colspan="2">–</td><td colspan="2">65.8</td></tr>
<tr><td>Yellow vein mosaic (% infested plants)</td><td colspan="2">74.40</td><td colspan="2">65.2</td><td colspan="2">58.7</td></tr>
<tr><td>Powdery mildew (% leaf damage)</td><td colspan="2">32.7</td><td colspan="2">–</td><td colspan="2">47.3</td></tr>
<tr><td>Root rot (% infested plants)</td><td colspan="2">–</td><td colspan="2">91.6</td><td colspan="2">52.6</td></tr>
<tr><td><i>M. incognita</i> population (population/250 ml soil)</td><td colspan="2">56.16</td><td colspan="2">60.88</td><td colspan="2">61.94</td></tr>
<tr><td>Nematode gall index</td><td colspan="2">60.00</td><td colspan="2">60.00</td><td colspan="2">80.00</td></tr>
<tr><td>Percent increase in natural enemies (coccinellid beetles, spiders, syrphids, and leafminer parasitoids)</td><td colspan="2">21.56</td><td colspan="2">14.32</td><td colspan="2">22.21</td></tr>
<tr><td></td><td>IPM</td><td>Farmer's practice</td><td>IPM</td><td>Farmers' practice[a]</td><td>IPM</td><td>Farmer's practice</td></tr>
<tr><td>Yield (t/ha)</td><td>20.90</td><td>17.00</td><td>19.63</td><td>–</td><td>17.00</td><td>15.12</td></tr>
<tr><td>B: C ratio</td><td>2.86:1</td><td>1.52:1</td><td>3.23:1</td><td>–</td><td>2.53:1</td><td>1.23:1</td></tr>
</table>

[a] Due to severe root incidence caused by *Macrophomina*, the crop was abandoned

Summary and Conclusion

In okra production, after the introduction of high yielding hybrids, there is increasing incidence of insect pests, diseases and nematodes which results in substantial yield losses. To mitigate the losses due to these pests, large quantities of pesticides are used in okra and it is observed that okra growers spray 10–12 times in a season. Therefore, the fruits that are harvested at short intervals are likely to have pesticide residues that are highly hazardous to consumers. Since the okra produce is harvested at short intervals and also consumed fresh in some cases, the adoption of IPM is essential to avoid the pesticide residues. It was proven that adoption of IPM benefited the farmers in both economically and environmentally sustainable ways.

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Chapter 8
Integrated Pest Management for Onion in India

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Abstract Onion is one of the major commercial vegetables in India, and the main limiting factor for higher production of this crop is the incidence of pests and diseases. To reduce the pesticide treadmill, efforts were made to evaluate five different onion IPM modules at Tamil Nadu Agricultural University in India. These include the bio-intensive module comprising of selection of healthy seed bulbs, bulb treatment with *Pseudomonas fluorescens* and *Trichoderma viride*, soil amendment with biopesticides and biofertilizers, foliar application of biopesticides, and need based application of chemical pesticides. These were found to be effective in checking onion pests and diseases. The onion IPM was further fine-tuned with additional IPM components, barrier crop of maize and pheromone and sticky traps. It was demonstrated in larger fields in farm holdings of Tamil Nadu under the Integrated Pest Management Collaborative Research Support Program (IPM CRSP) and now, IPM Innovation Lab of USAID during 2009–2013 through technology transfer programs viz., demonstrations, field days, radio, farm visits, publications and others. Impact

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assessment on onion IPM package revealed reduced production costs, increased bulb yield, and higher economic returns.

Keywords Onion pests and diseases • Shallot • Azadirachtin • *Pseudomonas flourescens* • *Trichoderma viride* • Pheromone traps • IPM module

Introduction

Onion, *Allium cepa* L. (Family: *Alliaceae*) is the fourth most important commercial vegetable crop cultivated in an area of 1,204,000 ha in India. Two main types of onion are being cultivated in India viz., Bellary onion or big onion (*Allium cepa* var. *cepa*) and multiplier onion or small onion or aggregatum onion or shallot (*Allium cepa* var. *aggregatum*) with the production and productivity of 19.04 million tonnes and 16.12 t/ha, respectively (www.nhb.gov.in). Maharashtra is the major producer of onion accounting for 30 % of the total production followed by Madhya Padesh, Karnataka, Gujarat, Bihar, Andra Pradesh, Rajasthan, Haryana and Tamil Nadu. In Tamil Nadu, onion is cultivated in an area of 39,970 ha with the production of 473,000 tonnes. The average productivity of onion in Tamil Nadu is 11.83 t/ha (www.nhb.gov.in). Pests and diseases play a major role in onion production leading to yield losses ranging from 10 % to 15 %. The annual export of onions from India has exceeded 1,358,000 tonnes during 2013–2014 worth Rs. 28,771 millions (www.agriexchange.apeda.gov.in). Presently the major markets for Indian onion are Sri Lanka, Dubai, Kuwait, Saudi Arabia, West Asia, Malaysia, Singapore, Bangladesh, Pakistan, Nepal, Maldives, and Quatar. Onion exports to Europe, America and Africa are almost non-existent, though many countries in these regions have large requirements. Through improved technologies combined with proper integrated pest management, the export potential of onion can be enhanced. The impact of major pests and diseases on onion production and productivity, the integrated pest management strategies developed for combating them and field experiences on the evaluation and demonstration of the IPM (Integrated Pest Management) package in Tamil Nadu, Southern India under USAID- Integrated Pest Management – Innovation Lab (IPM IL), are discussed in this chapter.

Major Pests and Diseases of Onion in India

Insect Pests

Onion Thrips (*Thrips tabaci*)

Onion thrips is generally considered as the key pest and the dominant species on onion *Allium cepa* L. (Linda and Whitney 2009). It is a polyphagous insect, which has spread to all continents and is recognized as an economically harmful pest of cultivated plants (Liu and Sparks 2003). Primary vegetable hosts include onion, garlic, leek, cabbage, cauliflower, bean, tomato, cucumber, and asparagus. Common field crop hosts include alfalfa, small grains, and cotton.

The life history consists of an egg, two active feeding larval instars and two relatively inactive non-feeding pupal instars designated as pre pupa and pupa (Lewis 1997). The adults are slender, yellowish brown, and measure about one mm in length. The nymphs resemble the adults in shape and color but are wingless and slightly smaller. Adult female longevity is for 2–3 weeks. The eggs hatch in 4–9 days. The nymphal period lasts for 4–6 days (Atwal and Dhaliwal 1997). The development cycle varies typically from 14 to 30 days, changing to 10 and 11 days when the temperature is over 30 °C (Ribeiro et al. 2009). Reproduction is entirely by parthenogenesis. Alston and Drost (2008) stated that a complete generation requires 3–4 weeks during the summer months and thus five to eight generations may occur each year.

Thrips cause an annual yield loss of 10–15 % in onion in India (Gupta et al. 1994). The nymphs and the adults feed mostly on green leaf tissue, causing direct damage by destroying epidermal cells. They feed by rasping and sucking the surface tissues and imbibing exuded cellular contents (Koschier et al. 2002). Crop quality is frequently impaired by thrips (Straub and Emmett 1992). During lifting, if there is a high population of thrips on leaves, they easily invade the onion bulbs and thus enter through the neck or splits in the skin. Finally they feed on the fleshy scales causing damage to the bulb which continues even during storage and in transit to export markets, lowering the quality and value of the onion (Workman and Martin 2002). Large numbers of thrips kill onion seedlings, while damage to older plants by thrips may cause crops to mature early and, subsequently reduce yields. Onion thrips feed under the leaf folds and in the protected inner leaves near the bulb (Yasodha and Natarajan 2008). During high population levels, they can also be found feeding on the exposed leaf surface. Thus both adults and nymphs cause damage, making the entire field to give a "silvery appearance". This severe scarring acts as an entry point for foliar disease pathogens (Fig. 8.1a, b and g).

The onion thrips, *T. tabaci* causes damage directly through feeding and indirectly through transmission of lethal plant viruses (Hardy and Teakle 1992). *Iris Yellow Spot Virus (IYSV)* causes lesions on onion leaves and flower scapes. The lesions are straw to tan colored, and spindle to diamond-shaped. Under some conditions the disease may spread rapidly causing plants to senesce early and dramatically reducing bulb size. Onion thrips is the only known vector (Nagata et al. 1999; Zen et al. 2008), transmission rates ranging from 33 % to 50 % (Kritzman et al. 2001) or 33–80 % (Doi et al. 2003) under experimental conditions. Distribution and incidence of *IYSV* infection in onion fields suggested that infected volunteer onions serve as an inoculum source for transmission by *T. tabaci* to onion crops (Gent and Schwartz 2004).

Fig. 8.1 (**a**) Onion thrips injury to shallot leaves. (**b**) Onion thrips infested shallot field presenting burnt up appearance. (**c**) Leaf-miner injury in shallot leaf. (**d**) Tobacco cutworm damage in shallot. (**e**) Symptom of basal rot infection in shallot. (**f**) Lesion in shallot leaf caused by purple blotch. (**g**) Combined infection of purple blotch and onion thrips

Leafminer (*Liriomyza* sp.)

Liriomyza is a highly polyphagous herbivore and a serious pest that attacks a wide array of vegetable and ornamental crops (Zhao and Kang 2002). The entire life cycle from egg to adult takes less than 3 weeks to more than 9 weeks depending on temperature and host plant. The feeding punctures can also serve as oviposition sites. *Liriomyza* females deposit their eggs (often many per leaf) at random on the leaf surface.

Females lay an average of 8–14 eggs per day. Eggs are laid singly but often in close proximity and only on the leaf surface. Larvae hatch from the eggs and feed in the spongy mesophyll of the leaf. Three larval instars develop in the leaf and the mines become progressively larger with each molt. The pupal stage lasts 7.9–12.6 days and the pupa varies in color from light brown to black. Adults are about 2.1 ± 0.2 mm long (Neder De Roman and Arce De Hamity 1984) with females being slightly larger than males. Females live up to 18 days and males about 6 days. The feeding and oviposition punctures made by adult females on leaves are points of entry for fungi and bacteria and the mining activity of larvae reduces the photosynthetic capacity of plants leading to drying of leaves and destruction of young plants (Unmole et al. 1999) (Fig. 8.1c).

Spodoptera litura

The tobacco caterpillar *S. litura* is one of the most economically important and regular polyphagous pests on field and horticultural crops (Shankara Murthy et al. 2006). According to Tandi and Narayanan (2002) it is distributed throughout India, causing serious losses when outbreaks occur, and it is capable of defoliating the entire crop. Atwal and Dhaliwal (2005) reported that the larvae feed on leaves and fresh growth. They are mostly active at night, cause extensive damage, particularly in nurseries as well as main fields. The incubation period varied from 2.5 to 5.5 days and the larval period varies from 14.6 to 18.1 days. The pupal period ranged from 9.2 to 12.0 days.

Spodoptera exigua

The beet armyworm *S. exigua* has been reported to attack 112 plant species belonging to 44 families, of which 40 species are known from India. Beet armyworms may completely destroy entire stands of onion seedlings and can stunt the growth of young plants (Anonymous 1992). During harvest stage, incidence of beet armyworm larvae results in economic loss by damaging and contaminating harvestable plant portions (Kerns et al. 1995). Kim et al. (1997) observed that *S. exigua* larvae after hatching immediately bore into the tube shaped leaves of the onion and then feed inside the skin of the tube. This behavior protects *S. exigua* from insecticide sprays and from its natural enemies (Fig. 8.1d).

Onion Fly (*Delia antiqua*)

Onion maggot is mostly restricted to cooler coastal climates where onions are grown on organic and muck soils. Its incidence is noticed in some parts of north India. The newly hatched maggots crawl below the soil surface and feed upon the roots or burrow into the basal plate of the bulbs. Injury sites on the bulb facilitate maggot entry. The full grown maggot enters the soil to pupate at a depth of 5–10 cm. Onion flies are slightly smaller than houseflies (Satyagopal et al. 2014).

Diseases

Basal Rot

Basal rot or bulb rot caused by *Fusarium oxysporum* f. sp. *cepae* is an economically important disease of onion and generally occurs when soil temperatures are very warm (optimum 29 °C) and where onion is continuously grown. Yield losses of 25–35 % to *Fusarium* basal rot have been reported in onion (Lacy and Roberts 1982). The disease occurs in patches with the initial symptom of yellowing and drying of older leaves followed by discoloration and necrosis of the basal plate. This symptom, in Tamil Nadu, India, is referred to as "*Kozhikkal*" meaning chicken foot as the affected plants with yellow leaves resemble a chicken's foot (Fig. 8.1e). As the disease progresses, the whole plant collapses or the leaves wilt successively from the outside of the plant inwards. Reddish or pinkish discoloration appears at the basal plate of onion, and since the roots are decayed, the affected bulb often detaches from the roots when the infected plants are pulled up. Later, due to the presence of secondary soil bacteria, the affected area rots. Sometimes the disease is enhanced by injuries or wounds in the bulb or in the root portion. Infected plants with rotted root systems can easily be pulled out from the soil. If infection occurs late in the season, due to latent infections, the symptoms may not show up until the onions are in storage (Brayford 1996). The fungus also causes decay of bulbs in storage and the losses during storage are generally more than that occurs in the field (Stadnik and Dhingra 1996). Though the disease is seen throughout the crop period, it is more conspicuous in a 30 day-old crop, particularly in the Kharif season (June–September).

The fungus infects onion bulbs through different ways viz., direct penetration of the basal plate (Havey 1995), roots or basal portions of older leaves (Shalaby and Struckmeyer 1966), wounding of the plant tissue by other organisms or by mechanical damage (Brayford 1996). For example, the pink root pathogen, *Pyrenochaeta terrestris*, can provide a mode of entry into plant roots. The fungus also infects weed species (Abawi and Lorbeer 1972) and other crops besides *Allium* (Tsutsui 1991). The fungus survives in soil for several years as chlamydospores or as a saprophyte on crop residues (Brayford 1996) and is spread by infected soil (Abawi and Lorbeer 1971), debris, irrigation water, farm equipment (Everts et al. 1985), onion bulb seed (Koycu and Ozer 1997) and onion transplants (Everts et al. 1985).

Damping Off

The disease caused by *Pythium* species is seen in the field when younger seedlings are killed before emergence from the soil (pre-emergence damping off) or when infected seedlings topple over after they emerge from the soil (post emergence damping off). Infection usually occurs in seedlings near the soil line and infected tissues become soft and constricted at the base and the plant collapses. The disease appears in circular patches in the field and is favored by ill-drained conditions due to stagnation of water, continuous rain or high soil moisture.

Downy Mildew

Downy mildew caused by *Peronospora destructor*, a serious foliar disease of onion during cool weather, attacks the plants at all growth stages, and infects all plant parts (Butler and Jones 1955). It occurs in two stages viz., the primary stage, when the infected bulb is planted and the secondary stage, when a healthy plant at leaf stage becomes infected from spores produced by the primary stage. The diseased plants develop pale areas on the leaves and die from the leaf tip to the basal portion, with the leaves folded downwards through the affected tissue. On the affected areas, a purplish grey velvety growth of the fungus is seen and this is most prominent in the early morning. Later, secondary black molds develop on the drying leaves. Infected plants collapse and die within a week if the conditions are favorable. The fungus also spreads from the leaf bases into the bulb, where it survives and is carried to the next season. It also survives in the soil as oospores (resting spores). Under favorable conditions, air-borne spores result in a rapid spread of the disease. High humidity, cool temperature (less than 22 °C), presence of free moisture from rainfall or dew and cloudy days favor disease development (Gupta and Paul 2001).

Pink Root

The disease is easily recognized by pink colored roots, caused by *Pyrenochaeta terrestris* (syn. *Phoma terrestris*). Infected plants are sporadically seen in the field with weakened or stunted growth and reduced bulb size. The infected roots turn light pink to red or purple, shrivel, become brittle and die. The pinkish red discoloration of roots may extend up to scales of the bulbs. Though the plant compensates to produce newer roots, these roots also become infected and die. Severely infected plants exhibit stunted growth with tip die-back and under sized bulbs. The pathogen does not affect the basal plate of the onion bulbs (Davis and Henderson 1937). Many weak species of *Fusarium* can sometimes cause pink roots, particularly on older roots, but the diagnosis of pink root can only be accurately accomplished on actively growing roots. Yield losses are greatest when plants are infected early in the season resulting in a poor root system that cannot keep up with water uptake during hot temperatures. The pathogen can penetrate onion roots directly without the need for wounds and less vigorous plants are most susceptible. Symptoms develop 7–21 days after infection. *Phoma terrestris* can survive for a very long time in soil and feeds on plant debris. It is most active at temperatures of 24–30 °C. Irrigation water and mechanical damage with farm implements promote the spread of the disease in the field.

White Rot

White rot of onion caused by *Sclerotium rolfsii* is observed both in the field as well as in storage. The disease occurs in patches in the field. Pre-mature yellowing and die-back of leaf tips are seen followed by destruction of the root system and rotting of bulbs. The affected bulbs and roots are covered with white fluffy mycelia with brown or black colored sclerotial bodies. The fungus is soil borne and the sclerotia persist in the soil for many years. The disease is favored by cool, moist soil with a soil temperature of less than 24 °C.

Purple Blotch

Purple blotch caused by *Alternaria porri* is a destructive foliar disease of onion particularly during cooler months as the disease spreads rapidly under favorable climatic conditions causing serious yield losses (Gupta et al. 1981). The loss in yield due to this disease is around 20–25 % and the severity of purple blotch in onion is always higher in fields with onion thrips (Thind and Jhooty 1982; Yasodha and Natarajan 2008). Infection starts as chlorotic areas on leaves which later turn to elliptical purple lesions up to 4 cm long bearing circular or oblong concentric black velvety rings of fungal fructifications. The lesions may girdle leaves/stalk and cause drying. The infected leaves gradually dry from the tip downwards, break, and hang down at the point of infection (Fig. 8.1f). Premature drying of foliage results in poor bulb development. Older leaves are more susceptible and the susceptibility of onion leaves to infection by *Alternaria porri* is influenced by leaf age and extent of injury caused by *Thrips tabaci*. Though older onion leaves are more susceptible to infection of *A. porri*, young leaves of plants infested with onion thrips are more prone to infection by the fungus. Hence disease severity levels are always higher on thrips infested plants (Fig. 8.1g). There is an association of infection by the fungus when the thrips population moves above the economic threshold level of 5/plant. The disease spreads through air-borne spores and seed bulbs collected from infected areas. The humid climate with temperatures ranging from 18 to 30 °C, relative humidity of 80–90 % and heavy dew favor disease development.

Integrated Pest Management Components

Onion growers in India generally rely on synthetic pesticides for management of pests and diseases and the frequency of applications ranges from six to nine sprays for short duration aggregatum onion with a duration of 65–75 days depending upon the season and pest and disease load (Selvamuthukumar 2011). Repeated synthetic pesticide applications often result in resistance development, resurgence and natural enemy destruction besides environmental degradation (Thanki et al. 2003). Hence, there is an immense need to develop proper integrated management practices to contain onion pests and diseases. The IPM components play a vital role in minimizing pressure on onion thereby reducing the environmental issues. The contribution of various IPM components in the Integrated Management of onion pests and diseases is discussed.

Cultural Practices

Field Sanitation, Plant Density and Crop Rotation

Broadleaf weeds and senescent crops may serve as sources of inoculum for insect pests and therefore weed destruction and deep ploughing of crop residues are recommended for insect pest management. Adult leaf miners experience difficulty in emerging if they are buried deeply in soil (Capinera 2001). Long rotations with unrelated crops, reduced plant density which reduces leaf wetness, and application of mancozeb or chlorothalonil are found to be effective against purple blotch (Miller and Lacy 1995). Closely spaced and densely planted onion crops developed more incidence of downy mildew as compared to widely spaced crops (Develash and Sugha 1997).

Bulb Selection

Selection of healthy bulbs for planting is important as the basal rot caused by *Fusarium* sp. is both a field and storage fungus (Coskuntuna and Ozer 2008). Basal rot incidence is one of the major causes for poor field stand as it causes rotting of the plant in the early crop growth stage. Healthy (disease free) seed bulbs are to be manually selected from stored seed onion before planting.

Mulching

Mulching has been reported to reduce thrips infestation considerably (Jensen et al. 2001). Straw or other mulch placed on the plant bed has been shown to reduce thrips populations and improve onion growth. Effects of mulch on thrips may include increased biological control through enhancement of predator populations, creation of a barrier for pre-pupae and pupae (resting life stages) to access soil, and reduced temperatures which slow thrips development and population increase (Alston and Drost 2008). Jensen et al. (2001) suggested that the enhancement of habitat for predators as a possible explanation for a decreased onion thrips pressure in straw mulched onion. Cultural practices such as mulching and staking of vegetables may influence both leafminers and their natural enemies (Capinera 2001). Larentzaki et al. (2008) indicated that populations of *T. tabaci* adults and larvae can be significantly reduced by the use of straw mulch without compromising overall onion yield. Jensen et al. (2003) suggested that straw mulching coupled with applications of spinosad and azadirachtin in an onion IPM program could significantly reduce the thrips population with higher yields and gross returns when compared to standard growers' practices.

Trap Crops and Barrier Crops

Intercropping with clover (*Trifolium*) reduces damage by onion thrips in field crops of both leek (Theunissen and Schelling 1998) and onion (Hildenhagen et al. 1995). Other crops that are highly attractive to onion thrips include carrot, crucifers, cucurbits, and some flowers (carnation, chrysanthemum). The trap crop is disked under or sprayed with an insecticide when the thrips population increases. Intercropping or mixed planting of carrots and onion has been shown to reduce the onion thrips population on onion by attracting them to the carrot. Castor, *Ricinus communis* being the most suitable host plant for *S. litura*, can be used as a trap crop to attract and destroy *S. litura* (Balasubramanian et al. 1984; Chibber et al. 1985). Deep ploughing immediately after harvest of the crop is helpful in exposing the resting stages of many insects, including cutworms, to their natural enemies like birds and to the action of sun and wind (Singh and Singh 2005). Growing maize as a barrier crop has been effective in preventing the entry of onion thrips to onion fields and in the conservation of coccinellid populations (Srinivas and Lawande 2002). Growing maize around field borders in onion has been reported to act as a barrier crop against thrips in onion (Dinakaran et al. 2013). Planting of a barrier crop of maize as two outer rows + one inner row of wheat on all four sides 7–10 days before onion planting has been found to be effective in reducing the thrips population on onion (Tripathy et al. 2014).

Fertilizer Management

Soil fertility management has an influence on thrips infestation and damage. According to Rateaver and Rateaver (1993) lack of adequate soil calcium may invite higher thrips populations and nutritional balance can reduce thrips attack. According to Malik et al. (2009) the maximum abundance of thrips (13 per plant) was observed in onion with high rates of nitrogen (200 and 250 kg/ha), which increased abundance of thrips as much as 73.9 %. The significant role of host management practices particularly in a combination of NPK @ 120:90:60 kg/ha, plant density of 0.5 million/ha and eight irrigations/season was found to reduce downy mildew incidence and increase the bulb yield of onion (Ahmad and Khan 2001).

Behavioral Approaches

Sticky Traps

Sticky traps of different colors, materials, and shapes have been used for sampling, monitoring and estimating populations and controlling various species of thrips, including *T. tabaci*, *T. palmi*, and *F. occidentalis* under greenhouse and field conditions (Terry 1997; Roditakis et al. 2001 and Szenasi et al. 2001). Generally, blue and white have been considered as the preferred or the most preferred colors for several species of thrips, including *T. tabaci* (Chu et al. 2000). Lu (1990) suggested that pale blue colored traps were the most attractive traps for onion thrips compared to the white, green, yellow, grey and red ones. Carrizo (2001) reported that the blue and white traps were more attractive for *T. tabaci* than orange and black traps. Demirel and Cranshaw (2005) reported that the neon yellow traps were significantly more attractive for *T. tabaci* than yellow, blue, neon green, silver and orange traps. According to Teulon et al. (2007) using sticky traps (without any olfactory cue) in onion crops to monitor onion thrips may provide an early detection tool, or possibly even a mass trapping system (Natwick et al. 2007).

Tryon et al. (1980) suggested the use of yellow sticky cards to sample adult leafminers in the genus *Liriomyza* and confirmed that yellow was more attractive to adults than other colors. Parrella et al. (1985) developed a sequential sampling plan using yellow sticky traps to monitor adult *L. trifolii* populations on greenhouse grown chrysanthemum. The sticky traps also functioned as a physical method to capture adult flies and could also be used as an additional component in an Integrated Pest Management Program against *Liriomyza* spp. in onions (Unmole et al. 1999). Yellow sticky traps have been reported to be effective in trapping onion thrips (Demirel and Cranshaw 2005) and leafminer adults (Unmole et al. 1999).

Pheromone Traps

Synthetic pheromones have been successfully utilized in a variety of ways in numerous agricultural systems. They have been used for mass trapping, disruption of mating communication, monitoring, and surveying. Against *S. litura and S. exigua*, synthetic pheromones have been found to disrupt the male moths' ability to locate pheromone point sources in onion and have resulted in large reductions in cutworm populations in treated fields. Sex pheromone traps are useful tools for monitoring, mass trapping and timing of insecticidal application in the management of cutworms, *Spodoptera* spp. in onion (Arida et al. 2002). The sex pheromone of female *S. exigua* has been identified and successfully used in pest population monitoring and management (Mitchell and Tumlinson 1994; Dong and Du 2002).

Host Plant Resistance

According to Alston and Drost (2008) there is no known "true resistance" in onion to thrips. However, some onion varieties can tolerate effects of thrips feeding with only mild yield loss. Varieties with tolerance to thrips require less insecticide application. Muhammad et al. (2004) evaluated the yield potential of six onion (*Allium cepa* L.) cultivars (Red Creole, Chiltan-89, Local, Sariab Surkh, White Globe and Local Kandhari) in a thrips infested environment. Local Kandhari followed by Sariab Surkh were the most susceptible to the thrips infestation while Chiltan-89 was the least. Out of 11 onion cultivars screened, pink roots were found on all the cultivars, including those considered to be resistant. The cultivars, Golden and Yellow Creole were highly susceptible to pink root whereas the cvs. Dessex, Granex, Laredo, Grano 502 and Grano (local) managed to grow and produce reasonable yields (tolerance), despite having infected roots (Levy and Gornik 1981).

Biological Control

Onion thrips are difficult to control with insecticides due to their small size and cryptic habits (Herron and James 2005). Hence, there is a need for an alternative control method such as the use of entomopathogenic fungi (Ugine et al. 2005). Some potential biological control agents of onion thrips have been identified in recent years. These include predators (Schade and Sengonca 1995), parasitoids (Murai and Loomans 2001) and entomopathogenic fungi (Hudak and Penzes 2004). Fejt and Jarosik (2000) explained the use of *Orius* species in combination with the predatory mites in biological control of thrips. Similar findings were reported by Ship and Wang (2003). Coll and Bottrell (1995) encouraged *Orius insidiosus* as a biological agent in the thrips niche. The entomopathogens viz. *Beauveria bassiana*, *Verticillium lecanii* and *Metarhizium anisopliae* have been reported to be effective against onion thrips through laboratory and field investigations (Almazraawi et al. 2009; Maniania et al. 2003).

Agromyzid leafminers are known to have rich natural enemy communities, particularly in their areas of origin, and much attention has been paid to augmentative biological control in glasshouses and classical biological control in the field with insect parasitoids (Minkenberg and van Lenteren 1986; Waterhouse and Norris 1987). Parrella et al. (1989) evaluated *Steinernema* nematodes for suppression of leaf mining activity. Hara et al. (1993) showed that high levels of relative humidity (at least 92 %) were needed to attain even moderately high (greater than 65 %) levels of parasitism. Work on *L. trifolii* has shown that nematodes can control the leafminer successfully and be used in conjunction with chemicals such as abamectin, provided that high humidity is maintained (Hara et al. 1993). Prijono et al. (2004) reported that cyromazine was relatively safe for the parasitoids of *Liriomyza*: *Hemiptarsenus varicornis*, *Opius* sp., *Gronotoma micromorpha*, and *Diglyphus isaea*. These species are common parasitoids of leafmining agromyzid pests (Konishi 2004), and therefore cyromazine can be utilized in a biological control program for the onion leafminer.

Some of the common parasitoids of *Spodoptera* sp. are *Chelonus insularis*, *Cotesia marginiventris* and *Meteorus autographae* (all Hymenoptera: Braconidae), and the tachinid *Lespesia archippivora* (Diptera: Tachinidae) (Ruberson et al. 1994). Capinera (1999) stated that several insect pathogens may prove to be useful for suppression of beet armyworm such as a nuclear polyhedrosis virus isolated from beet armyworm, a fungus *Beauveria bassiana* and entomopathogenic nematodes (Rhabditidae: Steinernematidae and Heterorhabditidae). Ground beetles are good predators of the onion maggot. Establishing grassy refuge strips in an onion crop will enhance the beetle population and reduce onion maggot populations (Anonymous 2012).

Zheng et al. (2005) reported that *Agrobacterium* mediated genetic transformation was applied to produce beet armyworm resistant tropical shallots. Transgenic shallot plants harboring the Cry1 Ca and H04 genes were completely resistant to the beet armyworm. *Spodoptera litura* nucleopolyhedrovirus (*Sl*NPV) is the most promising control agent and its efficacy has been established successfully against the pest in India (Muthuswami et al. 1993).

Bulb Treatment with Biopesticides

Pseudomonas fluorescens and *Trichoderma viride* have proven to be effective biocontrol agents against the basal rot pathogen (Malathi and Mohan 2011). These antagonistic organisms induce systemic resistance in plants and in addition promote plant growth (Bennett and Whipps 2008; Bennett et al. 2009). Karthikeyan et al. (2008) reported that onion bulb treatment with a consortium of antagonists e.g. *P. fluorescens* + *B. subtilis* + *T. viride* was found effective in promoting the plant growth in terms of plant height and bulb yield both in pot culture and field conditions. Onion bulb treatment with *P. fluorescens* (Pf1-TNAU formulation @) 5 g/kg + *T. viride*- TNAU formulation @5 g/kg) in 20 ml of water/kg of seed bulbs before planting was found to be effective in minimizing the basal rot incidence in aggregatum onion where the planting material is the bulb (Dinakaran et al. 2013). The biosuspension is to be sprinkled over the seed bulbs and manually turned for uniform coating of the bio-pesticides over the seed bulbs.

Soil Amendments with Bio-products

Field application of bio-pesticides reduces soil-borne pathogens like *Fusarium* and promotes buildup of antagonistic organisms and plant growth (Altintas and Bal 2008; Coskuntuna and Ozer 2008). Application of bio-fertilizers and Arbuscular Mycorrhizal Fungus (AMF) promotes plant growth and confers resistance to biotic stress (Srivastava and Tiwari 2003). AMF has been shown to increase resistance to root-infecting pathogenic fungi like *Fusarium* spp. and root invading nematodes (Lindermann 1994). Oilcakes e.g. groundnut cake and castor cake were found to be effective in checking the mycelial growth of *Alternaria porri* under laboratory conditions (Kumar and Palakshappa 2009). Bhosale et al. (2008) reported that among the plant products, *Lantana camara* and *Pongamia pinnata* were found effective in controlling Alternaria blight of onion. Application of AMF, *G. aggregatum* and the bio agent, *T. harzianum* ATh1 isolate checks the severity of white rot disease caused by *S. cepivorum* in onion. Hence, the use of these bio-control agents can be promoted as an active component of a bio-intensive Integrated Disease Management Program.

Neem cake application has been effective in checking pests and diseases besides promoting plant growth (Rukmani and Mariappan 1990; Chakrabarti and Sen 1991). Soil amendment with the bio-inputs *P. fluorescens* (TNAU formulation) @1.25 kg/ha), *T. viride* (TNAU formulation @1.25 kg/ha), Azophos (TNAU formulation of Azospirillum + Phosphobacteria @4 kg/ha), AMF (TNAU formulation @12.5 kg/ha) and Neem cake (commercial grade neem seed oil cake @250 kg/ha) mixed and applied uniformly in the field before planting was found to reduce disease incidence in aggregatum onion and increases yield (Dinakaran et al. 2013).

Foliar Application of Bio-Pesticides

Normally onion thrips infest shallots 4 weeks after planting. A foliar spray of *P. fluorescens* (5 g/l) and *Beauveria bassiana* (10 g/l) on the 30th day after planting has been found useful for the management of onion thrips in the early plant growth stage (Dinakaran et al. 2013). *B. bassiana* alone and in combination with other bio-pesticides has been reported to be effective against onion thrips (Thungrabeab et al. 2006; Almazraawi et al. 2009).

Botanical Pesticides

Neem oil, neem seed kernel extract and commercial formulations of azadirachtin have been found effective in controlling the thrips population in onion (Krishna Kumar et al. 2008). Malik et al. (2003) proved that *Calotropis procera* LI (Latex

Infusion) was best among the tested botanical insecticides with 42.67 % control against onion thrips and recommended that *C. procera* LI as effective as any other botanical insecticide in the management of onion thrips. Krishna Kumar et al. (2008) reported that NSKE (4 %) and acephate (0.1125 %) both reduced thrips numbers. Application of Azadirachtin 1 % (10,000 ppm) formulation @ 2 ml/l of water as a component of onion IPM has been reported to be effective in minimizing thrips and leafminer damage (Dinakaran et al. 2013). Sharma and Seth (2005) reported that the fertility of *S. litura* was significantly reduced after the treatment of azadirachtin. Shyam Sundar et al. (2000) reported that the lethal concentration of azadirachtin based proprietary formulations decreased egg hatchability of *S. litura*.

Evaluation of the Onion IPM Package

One of the challenges of developing and implementing an IPM package is to successfully balance the goals of reducing pesticide use while at the same time maintaining the crop quality demanded by the farmer and the market (Dinakaran et al. 2013). Tamil Nadu Agricultural University, with support from the Indian Council of Agricultural Research, evaluated the effectiveness and impact of five different IPM modules in managing the onion pests and diseases for two seasons during 2009 at Anbil Dharmalingam Agricultural College and Research Institute, Tiruchiappalli, Tamil Nadu, India. The modules with the different IPM components are described below.

Module 1: Bio- intensive package (Bio-pesticides – *Pseudomonas* based)
Module 2: Bio- intensive package (Bio-pesticides – *Trichoderma* based)
Module 3: Fine-tuned package (Biocontrol + Chemicals)
Module 4: Existing chemical package (As per TNAU Crop Production Guide)
Module 5: Farmers' practice (Chemical method)

Module I (Biointensive – Pseudomonas)

- Bulb treatment – *Pseudomonas fluorescens* (10 g/kg)
- Soil application of *Pseudomonas fluorescens* (2.5 kg/ha) + AMF (12.5 kg/ha) + Azophos 4 kg/ha + Neem cake 250 kg/ha
- *Beauveria bassiana* (10 g/l) on 30 DAP
- Azadirachtin 1 % (2 ml/l) on 40 DAP
- Need Based Application (NBA) of Profenophos (2 ml/l)/Endosulfan (2 ml/l)
- NBA of Mancozeb (2 g/l)/Tebuconazole (1.5 ml/l)/Zineb (2 g/l)

Module II (Bio-intensive – Trichoderma)

- Bulb treatment -*Trichoderma viride* (10 g/kg)
- Soil application of *T. viride* (2.5 kg/ha) + AMF (12.5 kg/ha) + Azophos 4 kg/ha + Neem cake (250 kg/ha)
- *Pseudomonas fluorescens* (5 g/l) at 30 DAP
- Azadirachtin 1 % (2 ml/l) at 40 DAP
- NBA of carbosulfan (2 ml/lit)/ Dimethoate (2 ml/l)
- NBA of Mancozeb (2 g/l)/ Tebuconazole (1.5 ml/l)/ Zineb (2 g/l)

Module III (Fine tuned bio-intensive)

- Bulb treatment – *Pseudomonas fluorescens* (5 g/kg) + *Trichoderma viride* (5 g/kg)
- Soil application of *Pseudomonas fluorescens* (1.25 kg/ha) + *T. viride* (1.25 kg/ha) + Azophos 4 kg/ha + AMF (12.5 kg/ha) + Neem cake (250 kg/ha)
- *Pseudomonas fluorescens* (5 g/l) + *Beauveria bassiana* (10 g/l) at 30 DAP
- Azadarachtin 1 % (2 ml/l) at 40 DAP & 50 DAP
- NBA of Profenophos (2 ml/l)/Acephate (1 g/l)
- NBA of Mancozeb (2 g/l)/Tebuconazole (1.5 ml/l)/Zineb (2 g/l)

Module IV (TNAU recommendations-chemical)

- Bulb treatment – Carbendazim (2 g/kg)
- Soil drenching with copper oxy chloride (2.5 g/l) – NBA
- Carbosulfan (2 ml/l) at 30 DAP
- Profenophos (2 ml/l) at 40 DAP
- Endosulfan (2 ml/l) at 50 DAP
- NBA of Mancozeb (2 g/l)/Tebucanozole (1.5 ml/l)/Zineb (2 g/l)

Module V (Farmers' Practice)

- No bulb treatment and no soil application of biocontrol agents/chemicals
- Spray application of only chemicals (insecticides/fungicides)

Among the five modules, Module III (Fine tuned bio-intensive) registered the lowest thrips population, basal rot and purple blotch incidence as against the highest incidence of pests and diseases in farmers' practice (Module V). The yield differed significantly and the Module III registered the highest bulb yield and cost benefit ratio (Table 8.1).

Table 8.1 Effect of different IPM modules on the management of pests and diseases of onion (Mean of two seasons 2009–2010)

Module	Thrips population (No./plant)			Basal rot (%)	Purple blotch (PDI)	Bulb yield (t/ha)	C:B[b]
	40 DAP[a]	50 DAP	60 DAP				
Module I	11.03	16.14	10.73	1.10	18.20 (21.93)[c]	16.2	1:2.53
Module II	10.47	17.52	13.74	1.20	18.90 (25.42)	16.3	1:2.54
Module III	8.92	12.44	10.50	0.75	18.45 (25.21)	17.2	1:2.65
Module IV	16.32	17.08	17.03	0.55	18.35 (25.04)	15.6	1:2.54
Module V	16.26	18.03	17.63	4.55	36.45 (37.01)	14.9	1:2.40
S. Ed.	0.43	0.58	0.50	0.45	2.20	0.34	
C. D. ($p = 0.05$)	0.94	1.26	1.08	0.95	4.78	0.75	

[a] Days after planting
[b] Cost benefit ratio
[c] Figures in parentheses are *arc sine* transformed values

Fine-Tuning and Popularization of the Onion IPM Package

In response to the threat of severe damage and economic loss by pests and diseases in onion, the USAID funded project IPM CRSP (Integrated Pest Management – Collaborative Research Support Program), in which Tamil Nadu Agricultural University, India was a collaborator (2009–2014), has developed an IPM package for onion (Gajendran et al. 2011; Dinakaran et al. 2013). Fine-tuning of the bio-intensive onion IPM module (Module III), evaluated earlier, consisted of the addition of certain IPM components e.g. barrier crop, traps, etc. The fine-tuned onion IPM package was test verified in farmers' holdings (large fields of 0.40 ha each) at the following seven locations from 2010 to 2013 in the major onion growing tracts of Tamil Nadu and compared with farmers' practice, where there was total reliance on synthetic pesticides (six to nine sprays in different locations).

Location 1: Irur, Perambalur District (*Rabi* 2009–2010)
Location 2: Ayyalur, Dindigul District (*Kharif* 2010)
Location 3: Alathur, Perambalur district (*Kharif* 2010)
Location 4: Sengattupatti, Trichy District (*Rabi* 2010–2011)
Location 5: Sathiramanai, Perambalur District (*Rabi* 2010–2011)
Location 6: Narasingapuram, Trichy District (*Rabi* 2011–2012)
Location 7: Padalur, Perambalur District (*Rabi* 2012–2013)

The fine-tuned onion IPM package consisted of the following components.

- Selection of healthy seed bulbs for planting
- Bulb treatment with *Pseudomonas fluorescens* (5 g/kg) + *Trichoderma viride* (5 g/kg)
- Soil application of *P. fluorescens* (1.25 kg/ha) + *T. viride* (1.25 kg/ha) + Arbuscular Mycorrhizal Fungi (12.5 kg/ha) + Azophos (Azospirillum + Phosphobacteria) (4 kg/ha) + Neem cake (250 kg/ha)
- Growing maize as a barrier crop
- Installation of yellow sticky traps @12/ha)
- Installation of sex pheromone traps (*Spodoptera litura and S. exigua*) @12/ha
- Foliar application of *P. fluorescens* (5 g/lit) + *Beauveria bassiana* (10 g/lit) on 30 DAP
- Foliar application of Azadirachtin 1 % (2 ml/lit) on 40 DAP
- Need Based Application (NBA) of profenophos (2 ml/lit) or dimethoate (2 ml/lit) or triazophos (2 ml/lit) for thrips/ leafminer/ cutworm management.
- NBA of tebuconazole (1.5 ml/lit)/ mancozeb (2 g/lit)/ zineb (2 g/lit) for purple blotch management.

Impact of Onion IPM Package

Pest and Disease Suppression

The onion IPM package evaluated under the IPM CRSP was found to be effective in minimizing major pests and diseases in the aggregatum onion as it increased bulb yields and provided a high cost benefit ratio at all locations. The overall mean of all the seven locations registered the reduced incidence of thrips (6.17 thrips/plant), leafminer (12.03 % damage), tobacco cutworm (3.21 % damage), basal rot (3.27 % incidence) and purple blotch (23.39 Plant Damage Index) in the IPM fields compared to farmer's approach, where there was a higher incidence of onion thrips (12.47 thrips/plant), leafminer (19.77 % damage), tobacco cutworm (5.92 % damage), basal rot (7.74 % incidence) and purple blotch (52.49 PDI) (Table 8.2) (Gajendran et al. 2014).

Yield and Cost Benefit

The IPM fields registered a higher mean bulb yield of 13.63 t/ha with a cost benefit ratio of 1:3.23 compared to 10.41 t/ha with a cost benefit ratio of 1:2.57 in the farmer's approach (Table 8.2). The additional budb yield of 3.22 t/ha realized in IPM field compared to farmers' practice has resulted in an additional revenue of Rs.48,300 per ha.

Table 8.2 Evaluation of an onion IPM package against pests and diseases (Mean of seven locations)

Module	Thrips population (no./plant)	Leaf miner damage (%)	Cutworm damage (%)	Basal rot (%)	Purple blotch (PDI)	Bulb yield (t/ha)	C:B
IPM package	6.17 (−50.52)	12.03 (−59.85)	3.21 (−45.78)	3.27 (−57.75)	23.39 (−55.44)	13.63 (+30.93)	1:3.23
Farmer's practice	12.47	19.77	5.92	7.74	52.49	10.41	1:2.57

Figures in parentheses are per cent decrease/increase over farmers' practice

IPM CRSP Technology Transfer Activities

Generally, the onion growers of Tamil Nadu, where the program was implemented, receive technical advisory services from the local extension functionaries of the State Department of Agriculture/Horticulture and Krishi Vigyan Kendras (KVK) (Farm Science Centers) of the State Agricultural University. However, these services are inadequate considering the complexity of the pest and disease problems and expertise available in the extension departments. The IPM CRSP team of the TNAU joined hands with the extension officials, KVK and All India Radio for speedy dissemination of the IPM package among the onion growers. Method demonstrations on seed bulb treatment with bio-pesticides, soil application of bio-inputs and neem cake, installation of yellow sticky traps and pheromone traps in the field were organized in all the locations to disseminate the eco-friendly technologies of onion IPM to the farming community. In all the seven locations, field days and exhibitions were organized at the time of harvesting to popularize the bio-intensive IPM module among the shallot growers. Farmer-Scientist interactive sessions and feedback (sharing of experiences) by the farmers who laid out demonstration trials were also organized. (Fig. 8.2)

To popularize the bio-inputs, *T. viride*, *P. fluorescens*, pheromone traps and yellow sticky traps among the onion growers, free distribution of these inputs was made to growers where the demonstration trials were conducted. Besides, pamphlets on the onion IPM package were prepared in the local language and distributed to growers for dissemination of the technology. Dissemination of the onion IPM package through publications in local newspapers and journals were made to popularize the technology among the shallot growers (Dinakaran et al. 2013).

Farm School on Radio

A Farm School program on Radio was organized under the USAID IPM CRSP involving the Directorate of Extension Education, Tamil Nadu Agricultural University and All India Radio, Trichy. A total of 1447 vegetable growers from all

Fig. 8.2 (**a**) Onion IPM demonstration trial at Sengattupatti village in Tamil Nadu. (**b**) Women farmer with harvested onion from IPM and Non-IPM plots. (**c**) Comparison of harvested onion from IPM and Farmer's practice plots. (**d**) Participation of IPM CRSP scientists in Field day organized at Irur village of Tamil Nadu. (**e**) Mini model of onion IPM module demonstrated to farmers at the exhibition. (**f**) Release of book on IPM in vegetable crops during Farm School Contact Programme

Fig. 8.2 (continued)

Fig. 8.2 (continued)

over Tamil Nadu state registered and benefited directly. Besides, the broadcast covered nearly 70 % of the area in Tamil Nadu state, benefiting thousands of onion growers. A book in the local language (Tamil) with the IPM package for vegetables including onion published with IPM CRSP funding was released on the occasion of the Farm School on Radio program and given free of cost to all the registered growers. (Fig. 8.2)

Impact on Farmers' Awareness and Adoption

An assessment of the impact of the onion IPM package demonstration and dissemination activities on the production and productivity of shallot revealed that the farmers realized a reduced production cost (2.60 %), increased bulb production (19.28 %) and higher economic returns (23.89 %) over the conventional farmer's approach where the total reliance was on synthetic chemical pesticides (Kiruthika 2013). The lack of IPM strategy in onion production was overcome through the IPM CRSP and it has been popularized in the major onion growing areas of Tamil Nadu, India. Though some of the progressive farmers adopted the entire package, a few major components of the shallot IPM module e.g. selection of healthy seed bulbs, bulb treatment with *Pseudomonas fluorescens* and *Trichoderma viride*, soil application of *Pseudomonas* and *Trichoderma* along with neem cake and spray application of azadirachtin were adopted by most of the onion growers in the region. The other components like growing of maize as a border crop and installation of traps have been adopted on a smaller scale. However, efforts were made to popularize all of these technologies in shallot growing areas under the IPM CRSP.

Conclusion

Onion is one of the most important commercial vegetable crops, giving a high remuneration for the growers within a short period, and any yield reduction due to pests and diseases will have serious economic impact on the livelihood of onion growers. Among the pests and diseases damaging onion, thrips, cutworms, leafminer, basal rot and purple blotch are considered very important under Indian conditions and attempts were made through the U.S. Agency for International Development (USAID) – Integrated Pest Management Collaborative Research Support Program (IPM CRSP) to disseminate onion IPM technology among the growers of Tamil Nadu state through large scale demonstrations, field days, farm school programs, etc. with reasonable success. Efforts are being continued to enhance the adoption rate of onion IPM technology to reduce the pesticide treadmill on onion coupled with pest and disease reduction and increased income for the growers.

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Chapter 9
IPM Packages for Naranjilla: Sustainable Production in an Environmentally Fragile Region

Jose Ochoa, Corinna Clements, Victor Barrera, Juan Manuel Dominguez, Michael A. Ellis, and Jeffrey Alwang

Abstract In Ecuador's Andean foothills, many colonists have planted naranjilla (*Solanum quitoense*), a perennial shrub and member of the section *Lasiocarpa* whose fruit is used to make a widely consumed juice. Naranjilla is highly profitable for small-scale farmers, representing one of the few economically profitable land uses in these environmentally vulnerable areas. However, naranjilla production in Ecuador is threatened by severe pest problems and the main solution—continual land-clearing—is environmentally unsustainable. The IPM CRSP invested more than 10 years of research to create an IPM package for naranjilla producers and this chapter describes the process of IPM package development, its components, and some of the potential impact of aggressive diffusion. The key constraint to naranjilla production a vascular wilt, which the IPM CRSP determined is caused by *Fusarium oxysporum*, is difficult to address through conventional control methods. As a result, hybrid and grafted varieties have been tested and released with uneven success. The CRSP helped develop a grafted version of the common variety and identified complementary pest-control techniques that, when combined with use of the grafted

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variety, can be used to produce economically and environmentally viable naranjilla fruits.

Keywords IPM • IPM CRSP • Ecuador • INIAP • Naranjilla • *Fusarium* • Grafting • Hybrid

Introduction

The frontier areas in the Eastern Andean foothills of Ecuador have been settled by colonists for decades. Colonization reduces population pressures in other areas, provides geopolitical stability, and has been used to displace populations afflicted by natural disasters (Long 1992). Although many settlers come in response to employment opportunities in oil and related industries, many end up farming. Unfortunately, the foothill areas are ecologically fragile, and suitable agricultural practices are needed to avoid problems associated with this fragility. Declining yields over time and subsequent conversion of recently cleared lands to pasture is common throughout the Amazon. The process of land clearing, short-term production of subsistence crops, followed by declining yields and conversion into pasture-based livestock production is responsible for the "hollowing out of the frontier" as commonly described in the literature (Rudel et al. 2002). The eventual decline in yields associated with the hollowing out is due to soil fragility, pest build-up and other production problems.

In Ecuador's Andean foothills, many colonists have planted Naranjilla (*Solanum quitoense*), a perennial shrub member of the section *Lasiocarpa* whose fruit is used to make a widely consumed juice. Naranjilla is highly profitable for small-scale farmers, and was produced in Ecuador on more than 5000 ha in 2010 (Revelo et al. 2010a). The fruit has high economic potential, particularly for export to markets in the U.S. and Europe, where consumers demand healthful, exotic fruit juices (Sabbe et al. 2013). However, the primary market for naranjilla is still domestic. Problems of low productivity and pesticide residues, in addition to susceptibility to several pests and diseases, have limited exports to levels far below their potential (Andrade et al. 2005; Sowell 2011).

Pests and diseases reduce the productivity of the naranjilla plant and contribute to land-clearing as producers clear pathogen-free forests for new plantations. Plants in new plantations during the 1960s produced up to 800 fruits per plant but disease epidemics started affecting naranjilla during the late 1970s and fruit yield subsequently decreased to as low as 40 fruits per plant (Oleas et al. 1990). More recently, the average yield reported for common naranjilla was 3,560 kg/ha (Revelo et al. 2010b), while with IPM technology, yields reach 28,380 kg/ha (Ochoa et al. 2010). The shortened productive life of the plant and reduced yields contribute to an increasing cycle of land conversion and extensive naranjilla cultivation, causing accelerated deforestation and consequent carbon emissions (Sowell and Shively 2012).

Deforestation associated with naranjilla cultivation is a particular concern because the Amazon region of Ecuador, where most naranjilla is produced, is a biodiversity "hotspot" (Myers et al. 2000; Sowell 2011). Deforestation in the Ecuador Amazon has been accelerated by oil exploitation and the Agrarian Reform Laws (1964, 1972), which encouraged the colonization and clearing of unoccupied forest land (Mecham 2001; Mosandl et al. 2008). Naranjilla is one of the few crops that could be profitable in the most remote colonized areas of the region (Bromley 1981) because growing conditions are ideal for the crop and few purchased inputs are required. Despite being a highly perishable crop, it ships well. In the 1990s, the Ecuadorian region had one of the highest deforestation rates in the Amazon, with around 2 % of existing forest lost every year, releasing large quantities of greenhouse gases (Mainville et al. 2006). In addition, runoff from soil erosion collects in streams, increasing the water's mercury content. This contamination harms the aquatic biosystem and poses a risk to human health through the consumption of fish containing toxic levels of mercury (Bertzky et al. 2010).

In order to help naranjilla growers deal with pests and diseases and to stabilize land use in this highly vulnerable area, a research project was begun in 1998 to study integrated pest management (IPM) options for naranjilla. Part of the global USAID-supported IPM CRSP,[1] work in Ecuador focused on three crops: potatoes in the highlands (covered in Chap. 10 of this volume); plantain and cacao in the coastal areas, and Andean fruits, particularly naranjilla, in the foothills. The objectives of this chapter are to: (i) discuss the promise of naranjilla cultivation in environmentally sensitive areas; (ii) describe a research program addressing pest-related challenges faced by producers; (iii) present and analyze a package of IPM practices for naranjilla; and (iv) discuss potential benefits of this package and some of the obstacles to its wide adoption in Ecuador.

Pest Constraints and IPM Research

When the IPM CRSP began its research in Ecuador, relatively little was known about production constraints of naranjilla, and the industry was in crisis. Local naranjilla cultivars such as "bola", "agria", "dulce" and "Baeza" were widely cultivated in the semi-tropical foothills into the early 1980s, when production of these native or "common" varieties began to slow and market prices rose. A hybrid variety named Puyo, which was much more resistant to the *Fusarium* vascular wilt that decimated the common varieties, aided greatly in restoring naranjilla cultivation in Ecuador. This hybrid was developed by Raul Viteri, who crossed *S. quitoense* with *Solanum sessiliflorum* (wild cocona) (Torre and Camacho 1981). Cocona is also a member of the section *Lasiocarpa* which has been domesticated in the low Amazon basin. However, a serious problem with Puyo is that its fruits are small, juice quality

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[1] CRSP stands for Collaborative Research Support Project, now known as the IPM Innovation Laboratory.

is low, and producers apply small quantities of the herbicide 2,4-D as a way of obtaining larger and juicier fruits. The hybrid varieties now found in Ecuadorean markets are of low quality and so contaminated with pesticide residues that export markets were effectively closed.

To address the small size of Puyo, a new hybrid was developed with a cross of the same species, but instead of wild cocona, the domesticated cocona Yanzatza was used as the female parent (Heiser 1999). This hybrid was released as INIAP-Palora (Fiallos 2000). A new hybrid called Espinuda, which appears to have developed spontaneously close to naranjilla plantings, is also grown in the Pastaza valley. However, neither INIAP-Palora, nor Espinudo have replaced the Puyo hybrid, and 2-4-D sprays remain an import limitation of naranjilla cultivation in Ecuador.

Fusarium Wilt

The IPM-CRSP prioritized work on naranjilla and early research, in partnership with scientists of the national agricultural research institute (INIAP, for its acronym in Spanish), focused on understanding the etiology of the vascular wilt plaguing the common variety. A preliminary diagnosis of naranjilla discovered a high incidence of "*Fusarium* wilt" in volunteer common naranjilla plants in hybrid parcels (Ochoa et al. 2001a). Subsequently, "*Fusarium* wilt" was found to be caused by the fungus *Fusarium oxysporum* (Ochoa et al. 2001b). Complementary pathogenicity studies showed that *F. oxysporum* is specific on naranjilla and a new form of the pathogen called *quitoense* was identified. The new taxonomic status of the fungus was therefore *F. oxysporum* f. sp. *quitoense* (Ochoa and Ellis 2002). Additional seed transmission studies demonstrated that *F. oxysporum* f. sp. *quitoense* is efficiently transmitted by seed (Ochoa and Ellis 2005). *Fusarium oxysporum* as a species is a soil-borne fungus that may persist in the soil for several years (Ignjatov et al. 2012). Root damage from the nematode *Meloidogyne incognita* increases the plant's susceptibility to infection from *F. oxysporum* (Sowell 2011). Once the soil is infested, farmers must move production to pathogen-free areas, typically by cutting primary or secondary forest (Ochoa et al. 2004; Sowell and Shively 2012; Andrade et al. 2005). Evidence shows that 68 % of naranjilla producers consider recently converted forest to be the best land for naranjilla cultivation (Alwang 2012). The pathogen is moved to these new plantations through infected seeds and farmers continue to move production to primary forests.

The project then pursued two viable management strategies: (i) use of pathogen-free seeds; and (ii) development of naranjilla varieties with genetic resistance. The project investigated different means of disinfesting infected naranjilla seeds. The production of certified disease-free seed is not practical in naranjilla growing areas where producers are widely spread and access by seed suppliers is limited (Buck and Alwang 2011). Laboratory tests with chemical alternatives showed that carbendazim in 2 g/l of water provided the best control and was most cost effective (Ochoa et al. 2010).

For several years, the use of carbendazim to disinfest seeds was the only viable means of controlling *Fusarium* wilt in common naranjilla. An INIAP bulletin and other outreach materials were developed to help spread this information. Due to the difficulty in reaching and communicating with naranjilla farmers, INIAP scientists recognized that resistance was the only long-term solution for controlling the disease, revitalizing common naranjilla plantations, and avoiding the cycle of land clearing, short-term planting, and subsequent abandonment.

In resistance studies, several accessions of the *Lasiocarpa* section of genus *Solanum* were found to be resistant to *F. oxysporum f sp.quitoense*; the resistance research then focused on the use of plant grafting as a possible solution to the wilt problem. An experiment using the common naranjilla cultivar "nanegalito" grafted into accessions of *S. hirtum*, *S. sessiflorum* and *S. candidum* found that the most favorable rootstock for the grafting was accession ECU-6242 of *S. hirtum*. Yields of 11,450 and 12,270 kg/ha were obtained in Tandapi and Saloya (Pinchincha province, Ecuador) in farmer fields (Table 9.1). An additional benefit of ECU-6242 is that it is resistant to the root-knot nematode (*Meloidogine incognita*), an important production constraint in *Fusarium*-infested fields (Pujota 2005; Revelo and Sandoval 2003). In further evaluations and validation studies using the full IPM package developed by INIAP, including control of other naranjilla pests, "Naneganlito" yields averaged 24,600 and "Tandapi" averaged 28,300 kg/ha (Ochoa et al. 2010).

Table 9.1 Reaction of a collection of the section *Lasiocarpa* exposed to *F. oxysporum* f. sp. *quitoense* and common naranjilla fruit yield (Nanegalito cultivar) grafted into this collection, and hybrids Puyo and INIAP-Palora. Tandapi and Saloya, Pichincha, Equador

Accessions	Vascular colonization[a]	Yield kg/ha[b]	
		Tandapi	Saloya
Solanum hirtum			
ECU-6242	R	11,454	12,269
GEP-001	R	7445	7238
Solanum sessiliflorum			
ECU-5552	R	8593	7852
ECU-7878	R	6015	5687
Solanum candidum			
GEP-005	R	10,775	2440
ECU-2086	R	–	6483
Varieties			
Hybrid Puyo	PR	–	2512
Hybrid INIAP-Palora	R	–	1618
Solanum quitoense	S	–	6288[c]

GEP Granja Experimental Palora

[a] *R* Resistant: absence of symptoms and/or limited vascular colonization; *PR* Partially resistant: some symptoms, long incubation period, signs of vascular colonization; *S* Susceptible

[b] Annual yield from four harvests

[c] Yields with applications of carbendazim

Late Blight

Once a solution to the major disease problem (*Fusarium* wilt) was obtained, the CRSP and INIAP scientists initiated studies on the second most important disease of naranjilla, late blight, caused by *Phytophthora infestans*. Late blight is an important constraint to naranjilla production in cooler production regions over 1,450 m above sea level, primarily in areas where humidity is high (Ochoa et al. 2001a). Symptoms are dark, watery spots on stems, young shoots, leaves and fruits. Since most infections occur on stem and young shoots, as few as nine infections per plant can cause 82 % yield losses (Ochoa et al. 2007). IPM CRSP research discovered that successful control of late blight involves continuous monitoring of the disease, and properly timed applications of effective fungicides. Fungicide evaluation showed that metalaxil and potassium phosphate were the most effective fungicides for control of naranjilla late blight (Ochoa et al. 2007). Although metalaxil is very effective, in order to avoid the development of fungicide resistance, application of metalaxyl is recommended for only one spray at the beginning of the epidemic, and especially if disease pressure is high. Use of phosphate fungicides, in combination with dimethomorph and cymoxanil alternated or rotated with applications of protectant fungicides such as mancozeb, chlorothalonil, captan and mandipropamid, is now considered to be the basis of naranjilla late blight control.

Fungicides should be applied every 2 weeks in times of high rainfall and every 3 weeks under drier conditions. Application should be directed to stems and sprouts where infections mostly occur, and on leaves only when infections occur. Mancozeb, chlorothalonil and captan should not be applied during harvest.

Ojo de Pollo

Anthracnose, locally named “Ojo de pollo”, caused by the fungus *Colletotrichum acutatum* is a common disease in all naranjilla varieties and hybrids especially at lower elevations. The disease mostly affects the fruit, but can infect sprouts, leaf veins and petals. Disease epidemics begin on the foliage; however, symptoms are only evident in the field on fruits. Therefore, as with late blight, disease monitoring and timely applications of effective fungicides are important control methods within the IPM program. The systemic fungicides difeconazole, triadimephon, azoxystrobina, and pentahydrate copper sulfate together with the protective fungicides captan and copper hydroxide were the most effective in vitro and in situ fungicides for anthracnose control (Jarrin 2009).

Anthracnose control should be mostly preventive. If the disease initiates before or during flowering, application of pentahydrate copper sulfate is recommended, followed by applications of protectant fungicides captan or copper hydroxide. During fruit setting and fruit development, difeconazole, triadimephon and pentahydrate copper sulfate rotated with captan and copper hydrocide fungicides are most effective at high humidity. Due to risk of fungicide resistance development in the pathogen, azoxystrobina should be applied only at fruit setting and under exceptionally high risk of disease development. At low inoculum pressure, captan and copper fungicides are sufficient during the dry season. Sanitation is an important cultural practice and is an integral part of the IPM program. It is important to remove all infected fruits from the plantation following each fungicide application. Azoxystrobina, pentahydrate copper sulfate, captan, copper hydroxide and mancoceb also control late blight, and are especially recommended when the two diseases occur simultaneously.

Bacterial Canker

A common challenge to the long-term sustainability of IPM programs is the need to identify control methodologies for newly emerging diseases. An example from the naranjilla-growing areas of Ecuador is bacterial canker, caused by *Clavibacter michiganensis* subsp. *michiganensis*, which was identified in farmer fields by the CRSP in 2008. The disease is not widespread, but when it emerges, it can cause significant losses if timely action is not taken. Symptoms are associated with plant wilt and include severe vascular necrosis. The bacterium is spread by seed; however, in naranjilla, the most important means of infection and disease spread is through contaminated tools. Unlike *F. oxysporum f.* sp. *quitoense*, this bacterium does not necessarily infect through roots, and is not a soil borne pathogen.

Disease epidemics of naranjilla bacterial canker in Ecuador have been mainly associated with grafting plants using infected knives. After implementing the practice of disinfesting knives with copper hydroxide, the incidence of bacterial canker epidemics has been greatly reduced. However, preventive control measures must be used because the disease can still be a threat to production. The main preventive recommendation is the use of seeds from healthy plants from orchards free of the disease. If disease free seeds is not guaranteed, seed disinfestation with sulfate of gentamicin and chlorhydrate of oxytetracycline or kasugamycin is an additional measure to take. In the field, sanitation (removal of infected plants and neighboring plants) and sprays with pentahydrate copper sulfate rotated with copper hydroxide are the main recommended controls.

Viability of the Grafted Naranjilla-Based IPM Program

The *INIAP Quitoense* is a grafted variety of naranjilla, developed by INIAP and the IPM CRSP, that is resistant to soil-borne diseases. The grafted variety is resistant to soil-borne diseases while maintaining the fruit quality of common naranjilla. The fruits of the conventionally-grown common (non-grafted) and the *INIAP Quitoense* are identical. The *INIAP Quitoense* consists of the *Baeza* variety of common naranjilla (selected for its high yields) grafted to rootstocks of *Solanum hirtum*, selected for its resistance to disease (Viteri et al. 2009). Prior to its release, the variety was tested on agricultural experiment stations and in farmer fields, and its productivity benefits are statistically and practically significant. The variety's resistance increases the plant's longevity and productivity. It can also be replanted on disease-infested land, reducing deforestation caused by continual land clearing to avoid the soil-borne diseases. In contrast to resistant hybrids, the grafted variety maintains fruit quality of the common variety, and prices of the fruits in markets are substantially higher than those of hybrid varieties (Clements et al. 2015). Despite its documented benefits, as with many new agricultural technologies, few farmers have adopted the grafted variety and (the technology should be more widely diffused).

Introduction and dissemination of grafted naranjilla varieties is complicated due to the need to either train grafting techniques to potential providers (i.e. decentralized grafters) or transportation of grafted seedlings to distant locations. Limited dissemination represents a lost opportunity to reduce deforestation, improve water quality and biodiversity and raise incomes of naranjilla farmers. INIAP leadership is interested in understanding the potential economic impacts of the *Quitoense* variety prior to investing further in diffusion efforts, and an ex-ante- impact assessment (see below) of the technology with the full IPM package was conducted.

Four major economic benefits of cultivation of the *INIAP Quitoense* are: (i) duration of the plant's productive life is increased, (ii) plants can be replanted in the same lot eliminating costs associated with land-clearing, (iii) yields are increased, and (iv) farmers benefit from higher market prices for common varieties compared to the hybrids. These benefits allow suppliers to reduce costs and increase supply to the market. In addition to these market-mediated economic benefits, use of grafted naranjilla reduces forest degradation and biodiversity loss, reduces environmental costs associated with pesticide application and runoff, and protects farmers' health.

Impact Assessment Methods

Aggregate economic benefits of the grafted naranjilla were calculated using partial equilibrium economic surplus analysis, a widely used process for measuring market-transmitted economic benefits. This method, discussed in Chap. 14 of this volume, accounts for benefits to producers due to reductions in the unit cost of production and benefits to consumers (and some losses to producers) due to a decline in market price associated with increased market supply of the common fruit. The formulae for computing economic surplus change are now well-known (Alston et al. 1995). Market-level impacts of the variety depend on (i) the expected proportionate yield increase per hectare after adoption of the new technology; (ii) the expected proportionate change in variable input cost per hectare; (iii) the elasticities of supply and demand; (iv) the land area under adoption and its time profile; and (v) the discount rate. Two adjustments were made to the standard method to account for irregularities in the production of naranjilla. The time profile of production costs had to be varied because the plant is a semi-perennial and the longer effective life of the grafted variety needed to be accounted for. The second adjustment was to account for the shift that would occur as land area planted to hybrid was shifted into the grafted variety over time. It is assumed that as the economic benefits of the grafted/IPM package become better known, farmers who currently plant hybrid varieties will shift to production of the grafted varieties. These adjustments are described in Clements et al. (2015).

Data and Parameters for the Impact Assessment

The basic building block of the surplus approach is the difference between the unit cost of production for the new variety compared to existing alternatives. This difference was computed using cost and yield data for three naranjilla varieties provided by INIAP researchers. Detailed production budgets were created based on information collected in randomized field trials conducted by INIAP researchers in Tandapi and Puyo, Ecuador for the common naranjilla, the *INIAP Quitoense* and the Puyo hybrid variety. The production budgets include costs for labor, equipment, chemical and other inputs for planting, maintenance, and harvesting, as well as capital costs (including land rental). Price information came from local markets and the Quito Central market as described in Clements et al. (2015). Area under production and quantities produced came from MAGAP (2014).

Interestingly, grafted naranjilla has the highest production cost during the first 18 months of production, partly due to the applications of fungicides in the IPM regime described (Table 9.2). However, this relationship changes over time. After 18

Table 9.2 Comparison of costs per hectare for common, hybrid, and grafted naranjilla over an 18-month production cycle

	Naranjilla variety			
Item	Common	Hybrid	Grafted	Details
Soil preparation	$745	$720	$814	Labor and material input costs for: Soil analysis, clearing land (including chainsaw rental), weeding, digging holes for planting
Planting	$1950	$1309	$2947	Labor and material input costs for: Seedlings (2000 per hectare); transport of seedlings; insecticides and fertilizer; hybrid costs also include costs of stakes
Plant maintenance	$2957	$3662	$3717	Labor and material input costs for: Fertilizing, weeding, pest and disease control
Harvest and post-harvest	$596	$758	$812	Labor and material input costs for : Harvest, sorting and transportation
Total costs	**$6248**	**$6449**	**$8290**	
Total yield (kg)	**9082**	**8396**	**11,720**	All quality types (first through fourth)

Source: Clements et al. (2015)

months, the *INIAP Quitoense* continues to produce fruit while the hybrid and common plants must be replanted. After 3–6 years, the *INIAP Quitoense*, because of its resistance to soil-borne pathogens, can be replanted on the same soil, avoiding the costs and environmental damage associated with clearing and preparing new land. As a result, the *INIAP Quitoense* provides more consistently positive income over time, avoiding the high costs of clearing land and reducing the frequency of replanting.

The impact assessment was conducted soon after the release the grafted variety and, as such, is ex-ante in nature. In the spirit of ex-ante impact assessments, total economic surplus was estimated for scenarios reflecting low, medium, and high rates of ceiling adoption (the maximum proportion of naranjilla land that would be planted to the grafted variety). A baseline adoption ceiling of 100 % was used for land currently under common naranjilla and 50 % ceiling was assumed for hybrid land. Two alternate adoption scenarios were simulated: one with 100 % adoption ceiling for both groups, another with only 50 % adoption by common producers and 25 % adoption by hybrid producers.

Results

The base scenario assumes that the *INIAP Quitoense* IPM package will strongly appeal to producers of common naranjilla, and uses a 100 % adoption rate (obtained over time) for this group. Hybrid producers are expected to be more resistant to adopting the *INIAP Quitoense*, as they are less familiar with the care required by the common plant. A 50 % ceiling adoption rate was assigned to this group. In this scenario, the change in total surplus over 20 years is $13.62 million, with a net present value of $6.55 million (Table 9.3). With the research and transfer costs that were estimated during the course of the research, the internal rate of return to the research

Table 9.3 Results for three levels of adoption

	Adoption levels						
Scenario	Common land (%)	Hybrid land (%)	Change in total surplus (‘000 $)	Net present value (‘000) in 2009 $	IRR (%)	Hectares of avoided deforestation	NPV of avoided deforestation for 60 tons/ha @ $5/ton (‘000) in 2009 $
Base	100	50	$13,623	$6550	30	17,289	$3672
Optimistic adoption rates	100	100	$28,566	$16,106	51	31,435	$6677
Pessimistic adoption rates	50	25	$6118	$1762	14	8645	$1836

Source: Clements et al. (2015)

is estimated to be 30 %. Producers gain more than consumers, taking 58 % of the total benefits. Producers gain from lower per-unit cost of production. These are mainly due to higher yields, longer productive lives and lower land-clearing costs. This suggests that adoption of this technology can have a significant impact on the livelihoods of naranjilla producers, who are poor and have few agronomic alternatives.

In addition to these market-mediated economic benefits, farmers who adopt the IPM package after producing the hybrid variety will accrue health benefits from no longer having to apply the chemical 2, 4-dichlorophenoxyacetic acid (2, 4-D). Furthermore, adoption of the *INIAP Quitoense* prevents deforestation. In the base scenario, up to 17,300 ha of land will avoid deforestation over a 20-year period as a result of the spread of the IPM naranjilla package. At 60 tons per hectare of carbon, a low estimate for carbon stored in below and above ground biomass in the Amazon, this translates to 1,038,000 tons of stored carbon. The average price of carbon credits from offset measures such as prevented deforestation was $5.00/t in 2010, a high $12.00/t in 2011, $7.40/t in 2012 and $4.20/t in 2013. Assuming the relatively low price of the base year of 2010, and using a discount rate of 5 %, the present value of the potential monetary value of this avoided deforestation is $3.67 million.

The economic, environmental, and health impacts from the *INIAP Quitoense* demonstrate that research on minor crops is worthwhile and important. Rates of return to this research, estimated in this paper, will not be realized unless efforts are taken to overcome barriers to adoption and more widespread diffusion of the grafted variety. Modest efforts at promoting diffusion will create economic and environmental benefits in all of the scenarios. Any diffusion program, however, will need to include training in skills to manage the grafted variety. *INIAP Quitoense* is a late maturing, big plant that needs climbing, and is more difficult to manage compared to the Puyo hybrid. Most farmers have become accustomed to Puyo cultivation and the switch to the grafted variety might take some time. For the higher benefits, however, INIAP *Quitoense* is promising, especially for progressive farmers. The costs of such outreach and their expected return in terms of adoption can be compared against the scenarios as a justification of public expenditure.

Summary and Conclusions

Naranjilla cultivation is one of the few livelihood options available to colonists in Ecuador's Amazon. These areas are environmentally fragile and, while conditions for growing naranjilla are optimal, disease pressure had decimated a once-promising crop. INIAP, with ongoing support from a number of projects, including the IPM CRSP, has developed a solid package of IPM practices to address biotic constraints associated with naranjilla production. An ongoing challenge in Ecuador is diffusion of information, particularly to remote areas where naranjilla production is found. Naranjilla IPM packages are complex but, because many of the recommended practices involve purchased inputs such as fungicides and grafted plantlets a promising path toward promoting naranjilla IPM might be through commercial input suppliers. These suppliers might be provided lists of recommended chemicals which they can then sell to the producers. Buck and Alwang (2011) found that knowledge of chemicals and their use was low in naranjilla producing areas and efforts to introduce IPM packages might be paired with more general programs to increase awareness of chemicals through commercial providers.

It is clear that any IPM approach needs to incorporate solutions to the principle biotic constraint—*Fusarium* wilt. The grafted variety is a short-term solution to this problem, but over the longer term resistance to the disease must be found and incorporated into a new common variety.

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Chapter 10
IPM Technologies for Potato Producers in Highland Ecuador

Vanessa Carrion, Patricio Gallegos, Victor Barrera, George W. Norton, and Jeffrey Alwang

Abstract This chapter describes a research and outreach effort to develop and diffuse IPM packages for potatoes in highland Ecuador. Potato production in Carchi is essential for livelihoods of small-scale producers and these producers face growing pest problems. The research project identified key pest constraints, worked with farmers and local scientists to develop and test appropriate IPM technologies, and created packages tailored to farmer needs. The research was especially relevant because farmers in the area were using large quantities of highly toxic chemicals as a part of their pest-control regimes and human and environmental health were suffering as a result. The partnership with an ongoing research-outreach effort, ability to leverage prior research findings, and participatory engagement of local stakeholders all contributed to the project's success. Emergence of new pests and changing potato market conditions are the main threats to long-term viability of the IPM packages, but they have spread into many potato farming communities in Carchi Province.

Keywords Ecuador • INIAP • Potatoes • Late blight • Andean potato weevil • Central American tuber moth

Introduction

Potatoes have been produced in Carchi Province in northern Ecuador for centuries. The province is the most important potato-growing area in the country, with 28 % of national production from plantings on only 13 % of total national potato area (SINAGAP 2012). Average yield in Carchi is significantly higher (17.9 tons/ha)

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than the national average (8.3 tons/ha). Agro-ecological conditions make Carchi an ideal location for potato production: soils are deep, loamy and high in organic content. The province receives regular rainfall and potato production is possible throughout the year. Supplemental irrigation is available for farmers when natural conditions fail.

In spite of the favorable conditions for producing potatoes, pests are severe constraints to potato production in Ecuador's highlands. Late blight (*Phytophthora infestans*), the Andean potato weevil (*Premnotrypes vorax*), and the Central American tuber moth (*Tecia solanivora*) have been prominent in Carchi since at least the mid-1980s. By the late 1990s, nearly 100 % of potato farmers in Carchi were affected by late blight, 80 % by the Andean weevil, and 6 % by the Central American tuber moth (Barrera et al. 1998). Farmers employ intensive applications of toxic chemicals to manage pests (Sherwood et al. 2005), and studies indicate that potato farmers in Carchi have become heavily dependent on pesticides (Yanggen et al. 2004). By the late 1990s, this dependency manifested itself in high input expenditures,[1] low profit margins, and evidence of negative health and environmental impacts (Crissman et al. 1998). Because of pesticide overuse and the potential human health and environmental costs of this overuse, a unique collaboration between national and international research[2] organizations, designed, tested, and conducted outreach on a package of IPM practices for potato producers.

The research and outreach program in Carchi, coordinated by the Ministry of Agriculture's (MAGAP) long-running Fortipapa[3] program, consisted of several components. A participatory appraisal, conducted in 1998 (Barrera et al. 1998), identified the major pests faced by Carchi potato farmers. This appraisal helped gauge farmer perceptions of potato pests, and use of control methods; outputs from the appraisal were used to prioritize research. The IPM CRSP program was able to build on prior research conducted by CIP and INIAP, and prioritized pest management technologies were tested on-station and in farmer fields. Randomized experiments were set up with an approved statistical design and farmer field trials ran for a minimum of 2 years to ensure that the results were not sensitive to weather or short-term anomalies.

Tested components included the following:

- Late Blight – use of certified and resistant seeds, field sanitation, crop rotation, and alternating low-toxicity fungicides to reduce resistance build up in the fungus

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[1] In 2003, it was estimated that pesticide expenditures represented between 12 % and 20 % of potato production costs in Carchi (Barrera et al. 2004)

[2] The Integrated Pest Management Collaborative Research Support Program (IPM-CRSP), funded by the United States Agency for International Development (USAID), was an important research partner in this effort.

[3] Fortipapa (*Fortalecimiento de la investigación y producción de semilla de papa en Ecuador*) began in 1992 with funding from the Swiss Development Agency (COSUDE). This project was a long-standing collaboration between MAGAP, Ecuador's National Institute of Agricultural Research (INIAP) and the International Potato Center (CIP).

- Andean potato weevil – monitoring and control using cardboard traps; use of bait plants; chemical control using low toxicity pesticides; alternative spraying practices to increase effectiveness and reduce use of chemicals, removal of all tubers at harvest, 30 day wait (host-free period) before replanting
- Tuber moth – monitoring insect populations, earlier planting, high hilling around plants, crop rotation, controls with low toxicity pesticides, seed solarization and application of low-toxicity and biological products prior to seed storage

Yellow fixed and mobile sticky traps were also investigated for control of a minor (in terms of damage) insect pest – the leaf miner (*Liriomyza huidobrensis*). Testing for the effectiveness of these components occurred primarily prior to 2003, when IPM CRSP potato research in Carchi ended. The Fortipapa program also ended around 2004 and most potato-related research activities conducted by INIAP in Carchi were suspended. Since then, Rhizoctonia (*Rhizoctonia solani*) appeared in the area and researchers have conducted a limited number of experiments to examine the effectiveness of seed disinfection and low-toxicity chemicals to control the disease (Travis 2015).

Development of IPM Packages: Field Trials and Experimentation

The preferred IPM package for potatoes combined cultural, mechanical, and chemical pest management methods. Recommended components were developed for each pest and disease, and development followed a standard protocol. Cultural controls help reduce the incidence of diseases and insect pests in the field. Examples include the use of certified and resistant seeds, high-hilling methods to create a barrier between insect pests and the tuber, and improved crop rotations. Mechanical controls are intended to kill a pest directly and include traps for monitoring and mass trapping of leafminer adults, and traps to target adult Andean potato weevil populations. IPM-related chemical control includes use of low-toxicity pesticides when other options are not available. Potato IPM chemical control practices include seed disinfection, directed-spray pesticide application to specific parts of the plant, and rotating use of fungicides with different active ingredients using low-toxicity pesticides.

Statistical evidence of the cost/benefit of the components and packages was obtained through field experiments. In some cases, individual practices were compared to a control and in others, components with known effectiveness were combined into a package and the package was compared to a control. The control was frequently the current farmer practice. Chemical alternatives were always compared face-to-face with alternatives that are more toxic; this was done to comply with the PERSUAP requirement associated with USAID funding.[4] Other components, like hilling during cultivation for control of the tuber moth were tested in combination with other practices, such as solarization of potato seeds and use of limited irrigation.

While several IPM packages built on earlier work conducted by Fortipapa, others were completely new. The fungicide rotation and resistant variety for late blight control were originally introduced to farmers by INIAP and CIP under Fortipapa; the IPM CRSP conducted final trials to ensure acceptability of the variety and refine the fungicide regime. The IPM CRSP trials compared the resistant variety (INIAP-Fripapa) to the most common existing variety (Superchola) and found that the former was associated with far less spraying (five versus nine for Superchola) and a 37 % reduction in chemical and spraying costs. The tuber moth package, however, involved a unique program of research supported by the IPM CRSP. During a participatory appraisal conducted at the start of the IPM CRSP, farmers made the research team aware that the most visible damage from the tuber moth occurred during seed storage. These perceptions of damage induced applications of highly toxic chemicals during storage. Since seed potatoes are stored in close proximity to kitchens, food storage, and locations where children play, finding effective means of reducing damage in storage was high on the list of project priorities. The research identified short-period seed solarization, followed by small doses of low-toxicity pesticides mixed with baculovirus as the best (most profitable) control method. The first research priority was to identify and test low-toxicity alternatives; these priorities were based on perceived cost savings and human health improvements from different research themes.

For the Andean potato weevil, the participatory assessment revealed that producers had good knowledge of the pest and the damage it causes, and, most importantly, the heavy use of highly toxic pesticides (Carbofuran was most common and has since been banned in Ecuador) for its control (Gallegos et al. 1997). The CRSP prioritized identification of low-toxicity compounds to be used against the adult insects, and these compounds were tested against a control, Acephate.[5] During these controlled experiments, biological control elements such as *Beauveria bassiana* and *Metarhizium anisopliae* were included. Relatively poor experimental results with respect to biological controls subsequently led to increased research to find appropriate strains of *Beauveria* and *Metarhizium* (see Table 10.1). Research continued to examine effectiveness of IPM techniques such as traps for the adult insect; this research involved the examination of different plant materials to include in the cardboard trap, combined use of biological controls (using *Beauveria bassiana*) and low-toxicity pesticides in the traps, and field spacing of traps. Over time, other practices were investigated and added to the recommended package as appropriate. In a final stage, the IPM package for the Andean potato weevil was tested on farmer fields against several alternative management practices.

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[4] The Pesticide Evaluation Report and Safer Use Action Plan (PERSUAP) was a requirement of all USAID-funded projects using significant amounts of chemicals. The purpose of the Plan is to comply with USAID regulations and to provide project personnel with tools to better manage field operations.

[5] Carbofuran could not be used as an experimental control due to the PERSUAP regulations.

Table 10.1 Tukey test at 5 % for *P. vorax* adult mortality through application of beneficial fungi. Santa Catalina. 2002

	% insect mortality at			
Isolate (place of collection)	5 days	10 days	15 days	20 days
Beauveria Huacona San José	29 a	100 a	100 a	100 a
Beauveria Chanchaló	25 a	100 a	100 a	100 a
Beauveria Sablog	10 b	65 b	78 b	90 abc
Beauveria Santa Catalina	7 bc	72 b	96 a	96 ab
Metarhizium Guano	7 bc	44 c	71 bc	80 bc
Beauveria San José de Minas	6 bc	31 d	69 bc	76 c
Metarhizium Santa Martha de Cuba	5 bc	27 d	57 c	80 bc
Metarhizium FCA-CADET	4 bc	32 d	70 bc	86 abc
Control zero	0	0	0	0
Coefficient of variation	38.52	9.71	11.75	9.85

Source: Barriga (2003). Note: the letters a, b, and c reading down the columns signify no statistically significant difference between treatments with the same letter. For example, at 5 days, mortality rates for isolate Huacona San Jose and Chanchalo are the same, and these rates exceed those of Sablog, etc.

As noted, the IPM packages employed combinations of methods and the statistical analysis built on complementarities between the practices. For example, the project discovered promising low-toxicity products for control of the Andean potato weevil. Field trials were established and the chitin inhibitor, Triflumuron, was identified as providing the best control with lowest cost and no negative environmental consequences. Triflumuron was subsequently tested as an insecticide in cardboard traps, and was used in trials for different spraying methods. In the spraying trials, various designs were investigated including a cross-hatch and applications directed to different parts of the plant. At the end of the experimental cycle, the IPM package included the low-toxicity alternative, chemical applications directed to the lower leaves on alternating rows of potatoes, and the use of Triflumuron in traps.

Economic analysis showed that the IPM packages were profitable compared to alternatives. Experiments were set up to evaluate different permutations of the packages and compared to standard farmer practices. The economic analysis showed that while yields between IPM and farmer field plots were not significantly different, cost savings associated with IPM were associated with $270–560[6] higher profits per crop per hectare. Given that two potato crops are possible in a year, this represents a substantial income gain to farmers (Mauceri et al. 2007). The cost breakdown shows that farm labor inputs are slightly higher with the IPM packages and seed prices can also be higher, while savings emerge from substantially less use of purchased inputs. These savings do not reflect other savings such as avoided health and environmental damage due to fewer applications of less toxic pesticides; human health improvements remain an under-investigated area of IPM research in the Andes. Several aggregate analyses of benefits showed that the IPM program for the Andean potato

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[6] In USD 2003.

weevil saved farmers $87 per hectare in the Central region and $42 per hectare in the South. The IPM program against the tuber moth in the North was projected to generate net benefits of $62 per hectare (Quishpe 2001; Barrera et al. 2002).

Outreach and Evaluation of Outreach Effectiveness

Diffusion of potato IPM in Ecuador was limited by factors specific to Ecuador and factors affecting IPM diffusion worldwide. In Ecuador, public agricultural extension was effectively discontinued in the early 1990s and, although the extension system has recently been revitalized by the hiring of hundreds of new extension professionals, at the time of the project there was no public agricultural extension. Almost all subsequent outreach efforts were in conjunction with funded projects and these projects needed to ensure that outreach was cost effective. IPM diffusion generally faces the following challenges: (i) IPM generally consists of complex packages that require substantial training; (ii) many IPM techniques are not amenable to private sector sales because of their public good nature,[7] and IPM must thus compete with profit-oriented private sector suppliers of pest control practices; and (iii) as pest resistance to insecticides develops, new technologies are needed thus requiring a dynamic research presence to maintain IPM adoption rates.

As a result of these challenges, the IPM CRSP continued with the Fortipapa emphasis on outreach efforts to facilitate IPM diffusion. Several outreach mechanisms were available. Farmer Field Schools (FFSs) are an intensive participatory training program, designed specifically to overcome IPM knowledge constraints (Feder et al. 2004). They involve weekly training sessions during a full crop season (Godtland et al. 2004). Field days are daylong events in which researchers demonstrate IPM practices and IPM packages to participants. Observation visits involve groups of farmers visiting other communities to gain exposure to IPM practices. Extension agent visits involve direct provision of information to farmers. Mass media methods include pamphlets, newspapers, and radio (Mauceri et al. 2007). All of these outreach practices were employed in Carchi and a key concern was to evaluate their effectiveness.

Between 1999 and 2003, 28 FFSs were conducted, many field days were held, and other outreach practices were instituted. Participants in a FFS were selected as based on their interest in participating and their willingness to share their knowledge and experiences with other farmers.[8] In the FFS, farmers and researchers met

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[7] IPM knowledge can be considered a public good, because if one farmer uses it, he/she cannot prevent other farmers from also using it; his/her benefits from use are also not affected by adoption by neighboring farmers. These conditions lead to the well-known outcome in the economics literature that the private sector will undersupply a public good.

[8] Farmers are purposively selected for participation in FFS, based on individual dynamism, willingness to learn and experiment, and leadership in the community. FFS provide intensive training to a few farmers, with the idea that this knowledge will spread due to the dynamism of the participants (Feder et al. 2004).

once per week during the 6-month potato growing season. Each session lasted approximately 3 h and combined practice- and theory-based learning; the idea behind the FFS is that farmers need to become aware of the life-cycle of the pest in order to devise and evaluate non-chemical control practices.[9] All farmers were invited to participate in field days. During the field days, attendees were taught low-intermediate complexity IPM practices using demonstrations, short lectures, and poster-based educational materials. Carchi stakeholders were also exposed to IPM through mass-media dissemination efforts including pamphlets, newspaper articles, and radio messages (Carrion et al. 2016).

An evaluation of training methods conducted in 2003 showed that IPM practices most commonly adopted by potato growers included: (i) modified crop rotations (58.7 % of farmers adopted), (ii) early harvesting (57.8 %), (iii) disposal of crop residues (50.5 %), (iv) seed disinfection (56.9 %), and (v) directed-spray pesticide application (48.6 %) (Mauceri et al. 2007; Carrion et al. 2016). Evidence from an evaluation of the effectiveness of IPM outreach/training methods show that participation in field days is positively associated with farmer IPM knowledge and has a statistically significant and strong impact on adoption of IPM. FFSs are expensive, but provide the most complete IPM knowledge and FFS participants in Carchi readily share information with neighboring farmers. Mass media is cheap, but only effective when used in combination with other more intensive training methods (Mauceri et al. 2007).

Since 2003, formal IPM training and outreach has disappeared from Carchi. While the INIAP office remains open, few outreach events have been held and no organized formal IPM training has occurred. Scattered research has been conducted on specific practices by INIAP, and these are related to newly emerging pests and diseases (e.g. *Rhizoctonia*) and not targeted at IPM packages.

IPM training in Carchi was abandoned due to resource constraints and this abandonment could have implications for continued spread of IPM. In the past decade, high potato price variability has become a serious problem for area farmers. Farmers in Carchi have decreased their land dedicated to potato production. In 2003, 8,600 ha were planted with potato in Carchi; by 2012, area planted had fallen by nearly one-half to 4,600 ha (SINAGAP 2012). Because of the uncertainty about the persistence of IPM knowledge and use, a study was conducted in 2012 to evaluate how IPM use and knowledge patterns changed in the province (Carrion 2013). A survey of 404 randomly selected potato farmers in Carchi was used to measure IPM knowledge, sources of knowledge and use of IPM.

Survey results show that farmers who participated in a FFS had the highest knowledge scores, followed by those whose main source of information was from field days. These differences are significant at the 5 % level (Table 10.2). Farmers

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[9] Evaluations of the FFS have shown that, immediately following the completion of the FFS, participants are more knowledgeable about pests and pest-management practices than non-participants (Feder et al. 2004; Gotland et al. 2004). There is very little evidence that this knowledge is durable. A recent review shows that FFS have changed agricultural practices and raised yields in pilot projects, but have not been effective when taken to scale (Waddington and White 2014).

Table 10.2 Main sources of IPM information and knowledge levels by source, Carchi, Ecuador, 2012

Main source of IPM information		Knowledge level by source		
Source	%	Low (%)	Moderate (%)	High (%)
No formal IPM training	7	29	71	0
FFS	18	10	85	5
Field days	17	15	82	3
Other farmers	35	27	72	1
Mass media	23	35	63	2

Source: Reproduced from Carrion et al. (2016)

Any training using FFS or field days occurred prior to 2003

Pearson $chi^2(12) = 22.13$ $Pr = 0.005$. The chi^2 test statistic is testing whether the paired observations on training and knowledge level by source are independent of each other. Independence is rejected at conventional levels of significance

without formal IPM training had limited knowledge of IPM, but a surprisingly high proportion of them had moderate knowledge. This is evidence that IPM knowledge continues to be widespread in Carchi. IPM knowledge retention clearly varies by information source and it increases with the intensity of the training program. FFS and field day participants are more knowledgeable and also more likely to retain this knowledge.

The survey also found that IPM use continued to be relatively widespread in Carchi even with the disappearance of formal training. Intensive use of IPM was lower in 2012 compared to when the project ended in 2003, but proportions of farmers in the low-medium adoption range increased.[10] The proportion of farmers in non- and low-adoption categories changed substantially between 2003 and 2012 (Fig. 10.1). In 2003, 30 % of farmers did not adopt any IPM practice, while by 2012 this proportion fell to less than 10 %. Non-adoption was largely replaced by low and moderate adoption, and by 2012, nearly 50 % of surveyed farmers were using at least a few IPM practices. The study also found that training method had a long-lasting impact on adoption; the proportion of farmers who participated in a FFS prior to 2003 who were in the low-moderate IPM class grew dramatically. In Carchi, IPM use has become more widespread, but even intensively trained farmers are now using relatively fewer IPM techniques (Carrion et al. 2016).

Even farmers with no formal training in IPM had adopted multiple practices by 2012. These farmers obviously learned from neighbors, many of whom had participated in a FFS. Adoption rates among those farmers with no formal training were generally lower than those farmers who had formal IPM training. Former FFS participants had the highest rates of adoption of practices that require more knowledge or that are more labor intensive such as traps for Andean potato weevil, and fixed and mobile yellow insect traps (Carrion et al. 2016). Many farmers reported "trying" IPM practices but abandoning them over time. Factors associated with high

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[10] IPM adoption is a continuum and the study constructed categories of adoption from low to high adoption based on the number and complexity of practices still in use (Carrion et al. 2016).

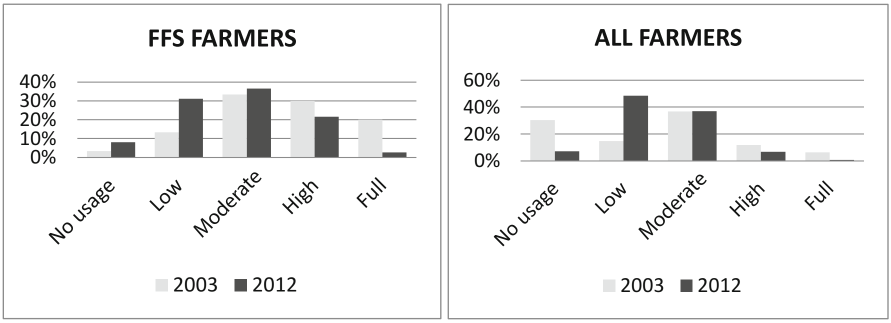

Fig. 10.1 IPM adoption over time, Carchi, Ecuador, 2003 and 2012 (Source: Mauceri et al. (2007) and Carrion (2013); n = 109 and n = 404, respectively. Reproduced from Carrion et al. (2016). Full usage corresponds to adoption of all recommended practices)

rates of abandonment included those requiring more intensive labor use. Others were abandoned because farmers viewed them as too complex, ineffective, or because they no longer felt threatened by the pest. Many farmers, for example, noted that leafminer populations had been declining, probably due to increased beneficial insects in the Province, and that yellow sticky traps were therefore no longer necessary (Carrion et al. 2016).

Lessons Learned

Due to long-standing pest pressures and intensive use of pesticides, Carchi, Ecuador was a good area for the introduction of a package of IPM practices. Prior research had indicated that pesticide applications had reached critical levels and economic and health consequences of pesticide overuse in potato production were evident. The participatory appraisal at project onset helped prioritize pest research and the project itself built on an impressive body of work by CIP and INIAP. This prioritization and good base of research allowed the IPM CRSP to move quickly into refinement and validation of packages. For example, Fortipapa had developed a number of potato clones with resistance to late blight; the IPM CRSP was able to avoid costly and lengthy research on the development of resistant varieties and instead focused on testing the improved clones for acceptance by local producers and consumers. Given the market orientation of Carchi potato producers, it was incumbent that any new variety be acceptable to local consumers.

In fact, potato breeding for resistance to late blight faces an ongoing challenge of consumer acceptance. The preferred late blight resistant variety developed by the Fortipapa program (INIAP-Fripapa) was released in 1995 and planting had spread to about 30 % of the potato area by 2003. However, by 2013, the variety was no longer planted in Carchi, supplanted by Superchola, which had been planted in Ecuador since before 1985. Superchola has better market acceptance, and for various reasons, INIAP-Fripapa certified seeds are no longer available in Carchi input markets. Given the challenges associated with resistance breeding and provision of certified seed, the research focus on fungicide rotations with low-toxicity compounds made sense.

Emergence of new potato pests, for example, *Rhizoctonia*, requires that IPM packages be adjusted over time. This emergence implies that even in areas where IPM packages have been tested and validated, it is still necessary to maintain a small maintenance research component. Potato pest challenges in Carchi may never be completely overcome and the natural response to the emergence of new pests is likely to be application of new chemical products. A national IPM program needs to be aware of these needs and the IPM research complex should be sufficiently agile to provide research outputs on a needed basis. Other threats to IPM include growing labor costs in many developing countries – researchers need to be aware that labor constraints may become increasingly binding over time and labor-intensive IPM practices may, as a result, become unviable.

Carchi is a place where pesticide use had become deeply entrenched and the persistence of IPM use shows that the intensive research-outreach program can have lasting impacts. In Ecuador, however, IPM producers have never taken advantage of growing markets for low-input products and IPM branding may be a fruitful avenue toward increased IPM uptake over time.

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Chapter 11
Integrated Pest Management of Vegetable Crops in Bangladesh

Md. Yousuf Mian, Md. Shahadath Hossain, and A.N.M. Rezaul Karim

Abstract Vegetable crops grown in Bangladesh suffer serious losses due to different insects and diseases. Before the introduction of IPM, farmers indiscriminately used different chemical pesticides to control vegetable pests. The IPM IL (CRSP), with active cooperation of Bangladesh Agricultural Research Institute (BARI) scientists, has developed different IPM packages for eggplant, cucurbitaceous crops, cabbage/cauliflower, okra and beans. IPM techniques developed include use of resistant varieties for eggplant to control wilting diseases, use of grafting, soil amendment with tricho-compost to combat soil borne diseases, pheromone trapping for the management of cucurbit fruit fly and eggplant fruit and shoot borer, infected shoot clipping in eggplant and release of bio-control agents for control several of pests.

Keywords Bangladesh • Integrated pest management • Vegetable IPM • IPM packages • Eggplant • Cucurbits • Cabbage • Cauliflower • Okra • Beans

Introduction

Being an agrarian country, Bangladesh's economy is largely based on agriculture which contributes about 18.6 % to the national GDP (gross domestic product), and employs around 45 % of the total labor force (BBS 2010). As it possesses a diverse agro-ecosystem and its soils are made up of nutrient-rich alluvium, numerous types of tropical and sub-tropical crops are grown in Bangladesh throughout the year. Although rice is the most important crop, vegetable crops play an important role in the economic development of Bangladesh. Millions of farmers earn their living by

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growing vegetables. Vegetable production contributes about 3.2 % to the agricultural GDP (BBS 2009). Over 100 kinds of vegetables are grown in the summer (Kharif) and winter (Rabi) seasons. Presently, however, improved vegetable varieties and cultivation practices developed by the national agricultural research institute have made it possible for farmers to cultivate more than 20 types of vegetables throughout most of the year. As a result, vegetable cultivation acreage and its production have increased significantly in recent years. During the 2010–2011 crop year, vegetable cultivation area occupied 451,808 ha that produced a total of 3,061,840 metric tons of vegetables (BBS 2011). According to an analysis of the FAO of the United Nations, as reported in the national Daily "Prothom Alo" of November 14, 2014, vegetable cultivation acreage during the last decade has increased annually at the rate of 5 %, and there has been a fivefold increase in vegetable production since the independence of Bangladesh. According to a report of the Ministry of Agriculture (Daily Prothom Alo of November 14, 2014), Bangladesh produced as much as 13,380,000 metric tons of vegetables during the financial year of 2013–2014. Although Bangladesh is still in deficit to produce enough vegetables for its own people, according to a report of UNCTAD (2008), Bangladesh exports about 54 different kinds of vegetables to different countries. During 2010–2011, Bangladesh earned about Tk. 3,169,859,000 (US$ 40,639,000) by exporting fresh vegetables (BBS 2011).

The agro-climate of Bangladesh is highly conducive to the proliferation of various kinds of pests, which act as the most important constraints to vegetable cultivation, and cause significant production losses every year. Although there is no actual estimate of the losses caused by pests, conservative estimates indicate 15–25 % annual yield losses depending on weather and crop type. In an effort to protect their vegetable crops from pest attacks, farmers have relied solely on chemical pesticides as no other alternatives were available to them. Therefore, indiscriminate use of pesticides has been a common practice in vegetable crops for many years. This has created various problems; development of pest resurgence, pest resistance to chemical pesticides, destruction of natural enemies, hazards to human health and environmental pollution. Keeping in view the above problems, activities of the IPM CRSP were initiated in Bangladesh in 1998 to develop and disseminate appropriate farm-oriented IPM technologies that would reduce pesticide use and reduce pesticide residues in crops, livestock, surface and underground water; increase farmers income; save agro-biodiversity; and increase women's role in IPM decision making and technology adoption. In this chapter, IPM approaches and technologies developed and disseminated in Bangladesh are described.

Common Vegetable Crops Grown in Bangladesh

More than100 different types of vegetables, comprising both local and exotic varieties, are grown in Bangladesh. Most of the vegetables are grown in the winter season (September–February). Some of the major winter vegetables are cabbage,

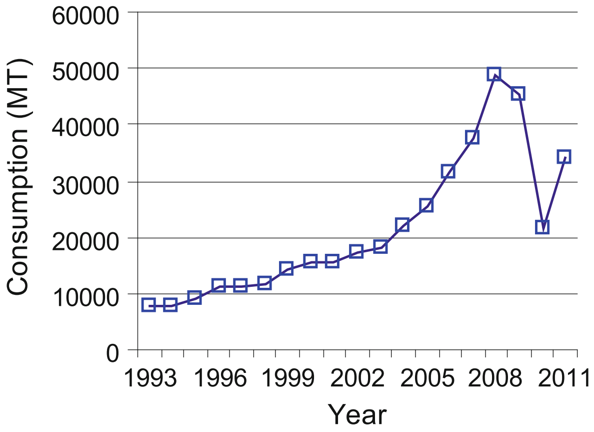

Fig. 11.1 Pesticide consumption in Bangladesh

cauliflower, tomato, eggplant, radish, country bean and bottle gourd, while some of the major summer (March–August) vegetables are pumpkin, bitter gourd, teasel gourd, ribbed gourd, snake gourd, ash gourd, okra, yard long bean, and Indian spinach. As mentioned earlier, many of the vegetable crops are presently grown throughout the year.

Crop Protection Scenario in Bangladesh

Crop protection in Bangladesh is mostly dependent on the use of chemical pesticides. Pesticides (mainly insecticides) for farmer use were first imported in Bangladesh around the mid-1950s and gained momentum in the early 1970s with the introduction of the green revolution which included the use of high yielding rice varieties. Before 1973, pesticides were imported by the Government and supplied to the farmers free of cost. In 1973 the subsidy was reduced to 50 % and it was totally withdrawn in 1979.

About 2 tons of pesticides were imported in 1956 and the quantity increased to about 8000 metric ton in 1993 (Rahman and Alam 1997). In 2000, after only 7 years, pesticide consumption rose to 15,632 tons. By 2005 it increased to 25,466 tons and in 2008 it rose to 48,690 tons (BBS 2011). Pesticide consumption increased about six times from 1993 to 2008. But after 2008, pesticide consumption started to decline (Fig. 11.1). This may be due to farmers' realization about the negative impact of pesticides and the wide publicity of the IPM concept throughout the nation.

Although 80 % of the insecticide is applied to rice, the intensity of insecticide application per unit area is highest in vegetables, especially in the high value vegetables. In rice, farmers usually apply insecticides three to four times per season, whereas in some high valued vegetables e.g. eggplant there are instances of more than 140 insecticide applications in a crop cycle. Profitable crops e.g. eggplant, country bean, cabbage, cauliflower, cucurbits, and tomato (summer varieties) usually receive excessive pesticide applications. There are even instances of daily applications of toxic pesticides especially during the rainy season. One of the most detrimental aspects of pesticide applications is the ignorance of the farmers about following the safety period between pesticide applications and crop harvest. Eggplant and many other vegetables are often harvested and marketed by some farmers within 6–12 h of spraying. As a result the vegetables and fruits that are harvested and marketed soon after pesticide applications contain residues that have potential to cause serious health hazards to consumers. Crops that are eaten fresh (for example, cucumber, tomato, lettuce) are very risky for consumers. Although some pesticides are broken down during cooking, some are temperature-stable and not affected by cooking, while some pesticides can become more hazardous after cooking. For example, the fungicide "mancozeb" after heating breaks down into carcinogenic ethylene thiourea. Moreover, repeated applications have induced multiple resistance in different pests against various pesticides. It is also suspected that fish and other aquatic fauna in open water bodies as well as in rice fields have been reduced due to the adverse effects of pesticide use. The serious consequences of pesticide use are well documented all over the world. In Bangladesh a survey of eggplant farmers in the Jessore region revealed that more than 98 % of the farmers are suffering from different side effects of pesticides.

Brief History of IPM in Bangladesh

In Bangladesh, Integrated Pest Management (IPM), which was then termed Integrated Pest Control (IPC), began in 1981 with the introduction of the first phase of Food and Agricultural Organization's (FAO) Inter-country Program (ICP) on rice. This program had two components: research and extension. The Bangladesh Rice Research Institute (BRRI) was responsible for the research that led to developing component IPM technologies for controlling rice pest insects and diseases, while the extension aspect was carried out by the Department of Agricultural Extension (DAE). After the first phase of FAO's IPM program, all other programs of FAO or other agencies were entirely extension-based. In the second phase, FAO extended the first phase program through the Regional Rice IPM-ICP project (1990–1996) under the leadership of Dr. S. Ramaswamy. Major emphasis of these projects was to develop IPM for the rice crop.

Extension-based programs for IPM in vegetable crops were initiated in Bangladesh during 1995 when five Farmer's Field Schools (FFSs) were conducted on eggplant and other vegetables under the umbrella of the Rice IPM-ICP project. The results from these FFSs showed significant reductions in pesticide use by eggplant IPM farmers. As a result, a sister project to the rice IPM-ICP, the Vegetable IPM-ICP, began in Bangladesh in August of 1996 and it was carried out for 3 years. The process of developing IPM in vegetables continued from 1996 to 2001 through a DAE-UNDP/FAO IPM Project, and from 1997 to 2006 through the DAE-DANIDA Strengthening Plant Protection Services (SPPS) Project in addition to the Rice IPM Project (FAO 2000).

For the first time in Bangladesh a research-based IPM program for vegetable crops was started in October, 1998 under the project name IPM CRSP (Integrated Pest Management Collaborative Research Support Program) with funding from USAID. The Virginia Polytechnic Institute and State University, (Virginia Tech), USA, has been acting as the management entity since the inception of the IPM CRSP project. Recently the name of the IPM CRSP has been changed to IPM IL (IPM Innovation Lab). From the very beginning of this project, the Bangladesh Agricultural Research Institute (BARI) has been associated as the main partner of the IPM IL (CRSP).

Recently, the IPM Innovation Lab started its fifth phase (2014–2019) in Bangladesh. Since the inception of the IPM CRSP project, the BARI scientists associated with the project developed a number of IPM technologies and packages for several crops e.g., eggplant, cabbage, cauliflower, tomato, beans, and different cucurbit crops. These packages are now being utilized in the farmers' fields throughout the major vegetable growing areas of the country, and these packages are also being demonstrated in different areas, under the auspices of the current IPM IL program, to promote farmers' acceptance. It is important to mention that before the inception of the IPM IL project no IPM technologies for farmer adoption were available in Bangladesh.

Vegetable IPM Inputs Available in Bangladesh

Supplies of necessary inputs and materials are a prerequisite for successful implementation of any IPM program. Because of the rapid adoption of IPM technologies by vegetable farmers in Bangladesh, several private agribusiness firms embarked on the business of manufacturing and supplying various IPM materials and inputs. Among the private companies and NGOs, Ispahani Agro-biotech Limited, and Gramin Krishok Shohayak Sanstha (GKSS) are prominent for producing and marketing of different IPM materials. Ispahani Agro-biotech Limited is marketing pheromones and beneficial parasitoids to monitor and control insect pests. For controlling the cucurbit fruit fly, Ispahani Agro-biotech Limited engaged in supplying the cucurbit fruit fly (*Bactrocera cucurbitae*) parapheromone under the trade name of "Q-phero (Culure)." This firm is also selling the eggplant fruit and shoot borer, *Leucinodes orbonalis* pheromone under the trade name of "BSFB Phero;" *Bactrocera dorsalis* parapheromone, Methyl Eugenol under the trade name of "Bacto-D;" and *Spodoptera litura* sex pheromone under the trade name of "Spodo-Lure." Recently, they started producing and marketing Tricho-compost, a bio-agent-fortified organic fertilizer, which can protect various crops, including vegetables, from several soil-borne diseases under the trade name of "Bio-derma." In addition, they are producing and marketing the egg parasitoid *Trichogramma chilonis* and the larval parasitoid *Bracon hebetor* on a limited scale. GKSS, a local NGO, has been

Table 11.1 Amount of different IPM products sold by Ispahani Agro-biotech Ltd. from 2009 to 2014

Year	Product name and amount sold				
	Q-Phero (cuelure)	BSFB Phero	Bactro-D (methyl eugenol)	Spodo-Lure	Bio-derma
	(# of pieces)	(# of pieces)	(# of pieces)	(# of pieces)	(MT)
2009	26,909	13,755	5521	–	–
2010	76,529	22,240	11,836	–	–
2011	80,362	24,617	10,854	–	–
2012	126,782	41,552	26,265	7500	
2013	334,550	124,580	67,340	12,500	0.56
2014	432,350	154,360	85,640	24,324	7.00

Table 11.2 Amount of tricho-compost sold by GKSS from 2009 to 2014

Year of production	Amount sold (MT)	No. of hectares covered	Approx. number farmer beneficiaries
2009	43	86	715
2010	220	420	3600
2011	260	520	4500
2012	240	480	4000
2013	252	504	4250
2014 (by Nov)	278	552	4633

producing and selling Tricho-compost since 2009. Farmers can purchase the above commodities from these organizations. A list of IPM products sold to the farmers in Bangladesh is given in Tables 11.1 and 11.2.

IPM Practices in Some Selected Vegetable Crops

Eggplant

Of the insect pests, the fruit and shoot borer, *Leucinodes orbonalis* is the most destructive and it may cause yield loss up to 85 %. The larvae bore into the shoots and cause them to wither. They also bore in to the fruits resulting in fruits that are not suitable for marketing and consumption. Refer to Muniappan et al. (2012) and Srinivasan (2009) for biology of this pest. Other pests that require attention are the leafhopper, *Amrasca biguttula biguttula*, thrips, *Thrips palmi*, leaf-eating ladybeetles, *Epilachna vigintioctopunctata*, *E. dodecastigma* and red spider mite, *Tetranychus urticae*. The leafhopper causes “hopper burn” on leaves by sucking the sap. Thrips feed on the leaves and cause silvery feeding scars on the lower surface and when they feed on the fruits they cause scarring and deformation. The adults and grubs of the spotted beetles feed by scraping the leaves. Spider mites cause white or yellow speckles on the leaves as they extract cell contents while feeding (Srinivasan 2009).

Of the diseases, the soil borne bacterial wilt caused by *Ralstonia solanacearum* is a serious problem in Bangladesh. Also root knot nematodes, *Meloidogyne* spp. are common and cause nodules in eggplant roots. Seedling damping off caused by *Ralstonia solanacearum*, *Fusarium* wilt and stem and fruit rot caused by *Phomopsis vexans* occur sporadically. Little leaf disease caused by mycoplasma is of minor importance.

IPM Package for Eggplant

1. Raising seedlings in sterile media and plastic trays to prevent damping off and other soil-borne diseases.
2. Soil application of neem cake to control nematodes.
3. Soil application of Tricho-compost before transplanting or treating seeds/seedlings with *Trichoderma* to control soil-borne fungal diseases.
4. Adoption of varieties BARI Begun-6 and BARI Begun-8 that are tolerant to BSFB.
5. Grafting seedlings on bacterial wilt resistant rootstock.
6. Setting up pheromone traps for fruit and shoot borer.
7. Clipping and destroying shoots affected by fruit and shoot borer.
8. Setting up yellow sticky traps.
9. Use of neem based formulations and other bio-pesticides.
10. Roguing little leaf infected plants in the field.
11. Release of the egg parasitoid, *Trichogramma* sp.
12. Adoption of conservation biological control.

Cucurbitaceous Crops

(Bitter gourd, bottle gourd, cucumber, musk melon, pointed gourd, and snake gourd)

Cucurbitaceous crops form the largest group of vegetable crops in Bangladesh, and melon fly *Bactrocera cucurbitae* (Diptera: Tephritidae) is a major pest. Eggs are laid in the fruit and the larvae upon hatching start feeding on the internal tissues of the fruits, resulting in total damage and fruit unfit for human consumption. Damage may reach up to 60 % in some crops. Mature larvae exit the fruits and pupate in the soil. The caterpillars of the cucumber moth, *Palpita* (*Diaphania*) *indica* (Lepidoptera: Pyralidae) attack leaves and sometimes cause defoliation and rarely attack fruits. Spotted beetles, *Epilachna* spp. are a problem only on some curcurbits like bitter gourd. The adults of pumpkin beetles, *Raphidopalpa* (*Alulacophora*) *foveicollis*, *R. abdominalis*, and *R. frontalis* (Coleoptera: Chrysomelidae) feed on leaves and the larvae on roots. Virus diseases *Pumpkin yellow vein mosaic virus* in bitter gourd and pumpkins, *Zucchini yellow mosaic virus* in snake gourd, *Papaya ringspot virus* in ash gourd and bottle gourd and root knot nematode *Meloidogyne* spp. are serious problems and *Fusarium* wilt, *Cercospora* leaf spot, and powdery mildew are of seasonal and minor importance.

IPM Package for Cucurbitaceous Crops

Technologies recommended for eggplant IPM 1, 2, 3, 6, 8, 9, 11 and 12 also apply to cucurbitaceous crops and the following additional technologies to be included are:

- Use of mashed sweet gourd trap

This trap consists of 100 g. ripe mashed sweet gourd mixed with 0.5 g Mipcin 75 WP or Dipterex 80 SP in 100 ml water. The bait is placed in a small earthen pot (about 12 cm diameter) which is located slightly above the crop canopy level. Another, slightly bigger earthen plate (about 18–22 cm diameter), is placed upside down at about 20–22 cm above it as a cover. Both the pots are cradled in a three split bamboo stick and firmly anchored in soil (Fig. 11.2). Mostly female fruit flies are attracted and killed in this trap. The bait materials in the MSG trap should be changed at 3–4 day intervals.

- Use of Cuelure trap to attract and kill male fruit flies.
- Sanitation: Removal of the pest infested fruits and burying them at least one foot deep in the soil.
- Roguing of virus infested plants in the field.

Tomato

Two important caterpillar pests are tomato fruit worm, *Helicoverpa armigera* and army worm, *Spodoptera litura.* The larvae of these insects feed on leaves and also bore into the fruits; however *H. armigera* causes more damage to fruits and *S. litura* to leaves. Both pupate in the soil. They are polyphagous. The leafminer, *Liriomyza* sp. is common but it is kept under control by parasitoids when chemical pesticides are not used. The cutworm, *Agrotis ipsilon* larva causes damage to the seedling in the seedbed as well as in the field by cutting them at the ground level during night. During the daytime the larvae remain hidden under the soil or in debris. The whitefly *Bemisia tabaci* causes damage by direct feeding on the leaves and by transmitting geminiviruses e.g. *Tomato leaf curl disease*. Recently the South American tomato leafminer, *Tuta absoluta* has established in the northern part of Bangladesh

Fig. 11.2 Mashed sweet gourd (MSG) trap

and surveys on its spread are being continued. Damping off in the nursery, bacterial wilt, *Fusarium* wilt, root knot nematode, late blight (*Phytophthora infestans*), and early blight (*Alternaria* sp.) in the field are common (Srinivasan 2010).

IPM Package for Tomato

Technologies recommended for eggplant IPM 1, 2, 3, 5, 8, 9, 11 and 12 apply to tomato and the following additional ones to be included are:

- Protecting seedlings with nylon netting to prevent whitefly infestation and virus disease infection (Fig. 11.3).
- Using BARI Hybrid Tomato – 4 for scion in grafting.
- Planting marigold as a trap crop for nematode control.
- Mulching and trellising.
- Setting up pheromone traps for *Helicoverpa* and *Spodoptera*.
- Augmentative release of the larval parasitoid, *Bracon hebetor* in addition to *Trichogramma* sp.
- Use of bio-pesticides such as *Bacillus thuringiensis*, *Beauveria bassiana*, *Metarhizium anisopliae*, and nucleopolyhedrosis viruses for *Helicoverpa* and *Spodoptera*.

Fig. 11.3 Seed bed covered by nylon net

Cabbage and Cauliflower

Cabbage and cauliflower are winter crops, but now some summer varieties are also available. Several insect pests including tomato fruit worm, army worm, diamondback moth (*Plutella xylostella* (Lepidoptera: Plutellidae), whitefly and aphids are major pests of these crops. Tomato fruit worm lays single eggs and the army worm in groups. Young army worm caterpillars feed on the outer leaves in groups, however grown up caterpillars of tomato fruit worm and army worm bore in the heads. Even though the diamondback moth lays single eggs it lays several eggs on each plant resulting in many larvae feeding on the leaves. Heavy whitefly and aphid populations on plants result in honey dew deposition and sooty mold development. Damping off disease incidence in the seed bed is a common problem. Other diseases include Fusarium wilt, leaf spot caused by *Alternaria* spp. and rotting caused by *Sclerotium* sp.

IPM Package for Cabbage and Cauliflower

Technologies recommended for eggplant IPM 1, 2, 3, 8, 9, 11 and 12 apply for cabbage and cauliflower and the following additional ones to be included are:

- Setting up pheromone traps for *Helicoverpa*, *Spodoptera* and *Plutella*.
- Augmentative release of *Trichogramma* sp. and *Bracon hebetor*.

- Use of bio-pesticides such as *Bacillus thuringiensis*, *Beauveria bassiana*, *Metarhizium anisopliae*, and nucleopolyhedrosis viruses for *Helicoverpa* and *Spodoptera*.

Okra

The major insect pest of okra is shoot and fruit borer, *Earias vittella* (Lepidoptera: Noctuidae). Eggs are laid singly either on young shoots or fruits. Larvae bore into the shoots and fruits and feed inside. The infested shoots wither and die and fruits become unmarketable. Whiteflies transmit *Bhendi yellow vein mosaic virus* disease which is widespread. Leafhoppers cause hopper burn symptoms on leaves and aphids build up to a high population on plants.

IPM Package for Okra

Technologies recommended for eggplant IPM 1, 2, 3, 7, 8, 9, 10 and 11 apply for okra and the following additional ones to be included are:

- Augmentative release of the egg parasitoid, *Trichogramma* sp.

Beans (Country Bean and Yard Long Bean)

Country bean and yard long bean are popular vegetables in Bangladesh. The bean pod borer, *Maruca vitrata* is the most serious pest. Eggs are laid singly on the flower buds and young pods. The larvae bore into the flower buds and pods. Bean thrips, *Megalurothrips usitatus*, the aphid *Aphis craccivora* and the spider mite, (*Tetranychus urticae* are the other pests that affect production. *Mungbean yellow mosaic India virus* in yardlong beans is common.

IPM Package for Beans

Technologies recommended for eggplant IPM 1, 2, 3, 8, 9, 11 and 12 apply for beans and the following additional one to be included is:

- Selection of disease free seeds for planting.

Technology Transfer Activities

Technology transfer activities were conducted with the financial support of USAID through a project entitled "Expansion of implementation of vegetable IPM Packages in Feed the Future Divisions of Bangladesh." Transfer activities including field demonstrations and field days were conducted through farmers' training activities. Field demonstrations of IPM techniques were conducted in farmers' fields to demonstrate the efficacy of IPM technology. Neighboring farmers were invited to observe the success of IPM packages in the demonstration fields.

Farmers' Training Programs

Farmers' IPM training targeted the production of different kinds of vegetables. Both male and female farmers were invited to attend the training programs. In the FY 2013–2014, 500 vegetable farmers (male 310 and female 190), were trained in IPM techniques in three districts of Bangladesh (Fig. 11.4). BARI scientists and IPM IL officers from the Bangladesh Site participated as resource speakers in the Farmers' training programs. Trainers addressed the identification of insect pests and natural enemies, virus disease symptoms, crop sanitation, preparation of Tricho-compost, grafting technology, staking and mulching for disease management of tomato, setting up pheromone traps, precautions for using pheromone traps and maintaining lures.

Field Demonstration of IPM Practices

IPM technologies were demonstrated in farmers' fields in several villages of Barisal, Faridpur and Jessore region during the summer (Kharif) and winter (Rabi) seasons of 2013–2014. In total, 74 villages under 11 upazilas of five districts were covered for demonstration of IPM practices (Fig. 11.5).

In demonstration fields, 3,416 pheromone traps and 609 yellow sticky traps were set in three regions. Among them, 1,259 sex pheromone traps and 288 yellow sticky traps were set in Jessore, 941 pheromone traps and 225 yellow sticky traps in Barisal, and 1,216 pheromone traps and 96 yellow sticky traps in Faridpur. Farmers were pleased to see more insects in pheromone traps and less infestation in their crops.

Fig. 11.4 Farmer's training program

Fig. 11.5 BARI and IPM IL scientists visiting a demonstration plot

Fig. 11.6 Farmers are being briefed on IPM practices before the field visit

Field Days

For disseminating IPM technologies, 24 field days were conducted on different vegetables such as eggplant, cucurbits, cabbage and cauliflower. A total of 2,400 (Male 1,727, Female 673) farmers and community leaders were present at these field days (Figs. 11.6 and 11.7). There they observed the performance of the pheromone traps, yellow sticky traps, and grafting technology and expressed interest in utilizing IPM practices on their farms.

Conclusion

Bangladesh has been highly successful in increasing its agricultural production and has almost attained self-sufficiency in rice production. Although Bangladesh is exporting some vegetables the country still needs to increase vegetable production to meet national needs. Average vegetable consumption by Bangladeshis is about 52 g of vegetables/day; this should be increased to 200 g/day to meet nutritional requirements. This can be accomplished through the introduction of new and innovative vegetable production technologies. The vegetable IPM farmers have significantly benefited by using a combination of pheromones and beneficial insects replacing use of chemical pesticides. To further increase production, soil nutrition and soil-borne disease management need to be considered. In this regard the use of

Fig. 11.7 Farmers visiting the demonstration plot in a farmer's field

Tricho-compost can play an important role in increasing soil nutrition and soil-borne disease management.

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Chapter 12
Development and Dissemination of Vegetable IPM Practices and Packages in Nepal

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Abstract Over- and misuse of chemical pesticides in vegetables in Nepal have brought about a renewed interest in Integrated Pest Management (IPM) both from public and research sectors. Through the support of the USAID-funded Integrated Pest Management Innovation Lab (IPM IL), full season IPM packages for important vegetable crops; tomato, cucumber and cauliflower were developed and evaluated at several locations during 2009–2014. IPM packages, which are holistic suites of IPM recommendations and practices, include seed/seedbed treatment using *Trichoderma*/*Pseudomonas*, soil solarization, roguing virus infected plants, use of nylon nets in the nursery, insect monitoring using pheromone traps, vegetable grafting against diseases, use of plastic trays and coco-peat, neem-based pesticides, bio-fertilizers, bio-control agents etc. IPM packages significantly reduce chemical pesticide use and are also economically competitive with farmer practices. In 2013, through an associate award from the USAID Mission, the Nepal program was extended to establish a structure to facilitate the technology transfer of IPM packages for high-value vegetable crops in the Feed the Future (FtF) districts in collaboration with the USAID KISAN project, and at the same time, to collaborate with private sectors to strengthen/support the supply chain of bio-products and IPM tools. More than 80 % of the farmers under the IPM IL and 42 % in the KISAN

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project have been recorded to have already adopted vegetable IPM practices and packages. Efforts to further expand and popularize IPM practices and technologies in vegetable growing areas are continuing.

Keywords Integrated Pest Management (IPM) • IPM packages • Nepal • Chemical pesticides • *Trichoderma* • Feed the Future • Cauliflower • Cucumber • Tomato

Introduction and Background

Nepal is a predominantly an agricultural country offering employment to about 67 % of the total population directly or indirectly and contributing 39 % of total Gross Domestic Product (GDP) (DoA 2013). Nepalese Agriculture is in the process of transformation from subsistence into commercial farming and has entered into the European market for export of high value crops like vegetables. Due to the variety of agro climatic regions and fertile soils, Nepal has potential to produce a wide variety of off-season vegetables of good quality and exporting them to neighboring countries. Thus, the Government has called for a shift from “cereals-led” growth to a more diversified production system such as vegetable crops (USAID report 2011). However, these policy advances have been hampered by vegetable insect pests that account for 30–40 % losses (Palikhe 2002; Jha and Regmi 2009). Consequently, vegetable farmers excessively use pesticides without any consideration of health and environment (Karmacharya 2012). Pesticide consumption is increasing by about 10–20 % per year and pesticide expenses in market- oriented vegetables and fruit production in Nepal are a major cost factor (Diwakar et al. 2008). In space of around 15 years, pesticide imported and formulated has increased by sevenfold; 50,000 kg in 1997/1998 to about 350,000 kg in 2011/2012 (Dhital et al. 2015). Realizing the importance and immediate need of providing small holder farmers with alternatives to chemical pesticides, the U. S Agency for International Development (USAID) funded Integrated Pest Management Innovation Lab (IPM IL) was designed to develop and implement a replicable approach to IPM to help reduce agricultural losses and at the same time maintain an ecological balance. It aims to support smallholder farmers particularly in tropical developing countries. IPM IL – Nepal is one of the country sites for the South Asia region IPM IL initiated in the year 2006. International Development Enterprises (iDE) is leading the program, with the Centre for Environmental and Agricultural Policy Research, Extension and Development (CEAPRED) as a major implementing partner. The program is also being supported by Nepal Agriculture Research Council (NARC), Department of Agriculture (DoA), Himalayan College of Agriculture Sciences and Technology (HICAST) and Agricare Nepal Pvt. Ltd. While the first phase (2006–2009) primarily concentrated on testing and verifying IPM components, the major thrust during the second phase (2009–2014) was to develop and test full-season IPM packages for important vegetable crops (tomato, cauliflower, cucumber), addressing major pest issues, and ensuring that the packages are economically and environmentally viable.

Research activities included on-farm field experiments on the evaluation of pest management components and developing IPM packages for specific vegetable crops. The IPM packages are holistic suites of IPM recommendations and practices, which include seed treatment with bio-agents, monitoring of pests and disease and establishing action thresholds for treatment, use of bio-fertilizers and need based application of bio-pesticides. The IPM packages significantly reduce chemical pesticide uses and are also economically competitive with farmer practices. Since 2013, through the associate award (AA) support to the Nepal program was extended to establish a structure to facilitate the technology transfer of IPM packages for high-value vegetable crops in the mid-western and far-western FtF districts. This present paper reviews the efforts made by the IPM IL-Nepal to develop and evaluate the vegetable IPM practices and packages and discusses the approaches used to disseminate verified IPM practices to reach a greater number of rural farmers.

The program was designed and implemented with an ecologically-based, participatory IPM strategy (Norton et al. 2005). The strategy included: (1) Participatory appraisals and farm-level surveys in focal districts, (2) Collaborative on-farm research to design and test existing and new IPM practices and packages, and (3) Cost benefit analyses of IPM packages. The extent of the adoption of IPM practices and technology packages is reported and the future thrusts are given. Finally, the lessons learned and recommendations are presented.

Participatory Appraisals and Farm-Level Surveys in Focal Districts

Participatory appraisals with key stakeholders involved reviews of existing pest management information and farm-level baseline surveys to prioritize pests and identify current practices and knowledge gaps as well as socioeconomic/policy constraints in the priority areas. The survey was conducted during the summer (May-August) of 2009 and was distributed among four districts of Nepal to capture the level of farmers' knowledge and pest management practices. The districts were selected in consultation with the Nepal Agriculture Research Council scientists. Each district selected was regarded as an important vegetable production zone in the country. The survey covered the following districts: Lalitpur, Kaski, Palpa, and Rupandehi. The study was descriptive and qualitative. A random sample of 100 farmers from each district was selected with assistance from the iDE project staff and agriculture extension officers. The majority of the farmers from this study represent small-holder farmers with small farm-enterprises, farm sizes and limited production resources. A questionnaire for the interviews was developed for the study. A mostly open ended questionnaire allowed farmers to freely give their opinion. Data were collected through mostly face-to-face interviews with help from

Table 12.1 Major insects and diseases identified from the study/assessment

Crop	Insects	Diseases
Tomato	Fruit borer (*Helicoverpa armigera*), tobacco cutworm (*Spodoptera litura*), whitefly (*Bemisia tabaci*), aphid (*Aphis gossypii*)	Bacterial wilt (*Ralstonia solanacearum*), virus (tomato leaf curl), damping off (*Pythium*/*Phytophthora*), root knot nematode (*Meloidogyne* spp.), late blight (*Phytophthora infestans*)
Cucumber	Red pumpkin beetle (*Aulacophora foveicollis*), fruit fly (*Bactrocera cucurbitae*)	Virus (mosaic), powdery mildew and downy mildew
Cauliflower	Diamondback moth (*Plutella xylostella*), cabbage butterfly (*Pieris rapae*), cabbage aphid (*Brevicoryne brassicae*)	*Alternaria* leaf spot, downy mildew,

extension officers and NARC scientists. Most questions centered on major insect pests in vegetables, farmers' awareness of pest management tactics, use of chemical pesticides and their perception toward the non-chemical approach as to pest management with a few questions on the socio-economic background of farmers.

Our findings revealed that most of the farmers used chemical pesticides to control pests on their farm and the applications were very intensive and frequent. Eighty percent of the farmers applied insecticide in their field on a calendar basis, twice a week, without any serious consideration for human health and the environment. Forty eight percent of the farmers expressed complete ignorance not having even the slightest knowledge of the availability of non-chemical approaches for reducing pest problems. And those who did know, were reluctant to practice non-chemical approaches in the absence of proper knowledge of the procedures and their effectiveness. Fifty two percent of the farmers interviewed were not using any protection measures while applying chemical pesticides. Our results also implied that the selection of pesticide types, dosage and mode of application, was mostly based on agro-chemicals dealers' recommendations (39.3 %) followed by those of government offices/officers (30.4 %). In most cases (around 55 %), farmers did not read pesticide labels nor were they aware of pre-harvest intervals (PHI). This was partly due to the fact that the majority of them were illiterate and thus they were forced to depend wholly on traders for the information (who in most cases are unregistered and are selling the pesticide in village 'kiosks'). These results call for an intensive training of farmers on reducing dependence on chemical methods for pest control.

Most of the farmers (vegetable) experienced a wide range of pest problems on vegetables. Almost all farmers (95 %) admitted that in the last few years the infestation of insect pests has increased and managing the pest population has become increasingly difficult. Almost all the farmers (96 %) believe that it is practically impossible for them to grow crops without use of any chemical pesticides. A detailed list of major pests identified for the vegetables is presented in Table 12.1

below. Furthermore, farmers indicated that sucking pests on tomato e.g., whitefly, jassids (leafhoppers) and red spider mites have risen to the status of major pests, previously being a minor problem. All (100 %) eggplant producers indicated that the eggplant fruit and shoot borer (EFSB) is the major threat, almost year round, but causes greatest loss during the summer (50–60 %) in comparison to the winter (less than 10 %). These data are in agreement with additional information provided by local scientists and extension agents.

Collaborative On-Farm Research to Design and Test Existing and New IPM Practices and Packages

From 2010 onwards IPM components and packages were tested, in close coordination with scientists and project staff, in the four districts mentioned above. To test the effectiveness of different IPM components, replicated on-farm trials with randomized treatments, and farmer's practice as the control, were conducted in each of the target districts. Randomized controlled trials (RCTs) were used to assess impacts with and without IPM (Khandker et al. 2010). For testing IPM components (Table 12.2), farms with similar pest problems and growing conditions were paired and results for farms implementing IPM packages were compared with results from control farms. For statistical validity, each on-farm trial was conducted for a minimum of 2 years. Pests, pesticide use and crop yield were measured in IPM treatments and compared to the control as a measurement of IPM effectiveness. Below are the major IPM components tested and verified, which were consolidated into IPM packages based on the on-farm participatory research.

Table 12.2 Major IPM components for vegetables

Components	Tomato	Cucumber	Cauliflower
Seed treatment with *Trichoderma viride* (4 g/kg)	X	X	X
Seed treatment with *Pseudomonas* @ 10 g/kg of seed	X	X	X
Use of plastic trays and coco-peat	X	X	X
Nursery + seedling dip treatment with *Pseudomonas* @ 10 g/L of water	X	X	X
Use of grafted seedlings	X		
Roguing virus infested seedlings/plants	X	X	X
Marigold as a border crop	X		
Use of nursery nets to prevent insect vectors	X	X	X
Use of yellow sticky traps	X	X	X
Pheromone traps (*Helicoverpa*, *Spodoptera*)	X	X	X
Application of neem products (Azadirachtin based formulations/NSKE 5 %)	X	X	X
Need-based application of bio-pesticides	X	X	X

In each location, the micro plots served as replicates for each treatment and observations in each location were compared statistically by the paired t-test. The mean values of pest and disease incidence, yield and economics of each location were treated as replicates and the overall mean of locations were compared statistically by ANOVA.

Tomato

Tomato IPM experiments, conducted in farmer's fields at four sites in each of the four districts during 2010–2013, were segregated under IPM plots and Farmers' plots (FP). Plastic trays with coco-peat were used as a nursery medium. At all the sites two nurseries were developed: one using plastic trays and coco-peat (IPM treatment), and the other one in soil (farmers' practice). The comparative germination percentage of the seedlings was recorded. *Srijana* variety tomato was used in all trials. The soils at all the sites were medium textured sandy loam. Crops were irrigated regularly as per need. Plots were of similar size (100 m^2) at all sites.

Germination percentage (75.16 ± 0.18 vs 68.9 ± 0.14) and yield (36.72 ± 1.03 vs 30.12 ± 1.07) were higher in case of IPM plots in comparison with the normal farmers' practice. Similarly, there was reduced incidence of the major insect pests and diseases, with reduced chemical sprays in the case of IPM practice (Table 12.3).

Table 12.3 Impact of tomato IPM packages in comparison with farmers' practices

	Treatment 1 (IPM practice)	Treatment 2 (farmers practice)
Particulars	Mean ± (SE)	Mean ± (SE)
Germination percentage	75.16 ± 0.18	68.9 ± 0.14
Diseases		
Damping off after transplanting seedlings in field (%)	6 ± 0.05	13 ± 0.08
Early blight (% of infested plants)	4 ± 0.03	8 ± 0.04
Late blight (% of infested plants)	36 ± 0.08	54 ± 0.12
Bacterial wilt (% of infested plants)	6 ± 0.03	18 ± 0.06
Root knot nematode (% of infested plants)	4 ± 0.03	8 ± 0.04
Tomato leaf curl virus (% of infected plants)	14 ± 0.05	24 ± 0.08
Insect pests		
Aphid population (in 5 leaves/plant)	8.40 ± 0.34	13.60 ± 0.28
Whitefly population (no./leaf)	3.40 ± 0.14	6.27 ± 0.23
Tobacco cutworm (no./leaf)	5.07 ± 0.23	14.13 ± 0.27
Fruit borer (% fruits/shoots infested)	5.20 ± 0.24	24.53 ± 0.23
Pesticide sprays (no.)	2 ± 0.17	7 ± 0.11
Crop yield (t/ha)	36.72 ± 1.03	30.12 ± 1.07

Cauliflower

Cauliflower trials, conducted during September to December 2010–2013, were segregated into IPM plots and Farmers' Plots. Cauliflower variety *Snow Mystique* was used in all the trials. Seedlings were transplanted at same time in both plots during the last week of September. To grow the healthy seedlings, plastic trays filled with coco-peat were used as the medium. Soils at all the sites were medium textured sandy loam. The area under all the trial sites was similar (100 m^2).

The germination percentage of seedlings in IPM plots was found higher (75 ± 0.21) compared to that of the Farmers' Practice (FP) (68.25 ± 0.19). On visual observation, cauliflower seedlings under IPM Practice were healthier and their growth more vigorous. Similarly, the crop yield in the IPM plot was significantly higher (15.78 ± 0.32) than that of FP (13.57 ± 0.21). Moreover, the insect and disease infestation was lower in the IPM plot in comparison with the FP (Table 12.4).

Cucumber

Cucumber trials, conducted during February to June 2010–2013, were segregated into IPM plot and Farmers plot. Malini variety of cucumber was used at all trial sites. The area under all the trials was similar (100 m^2). Seedlings were transplanted during the second week of February. Results (Table 12.5) indicate that the germination percentage and yield were both higher in case of the IPM practice compared

Table 12.4 Impact of cauliflower IPM packages in comparison with farmers' practice

Particulars	Treatment 1 (IPM practice)	Treatment 2 (farmers' practice)
	Mean ± (SE)	Mean ± (SE)
Germination percentage	75 ± 0.21	68.25 ± 0.19
Diseases		
Damping off after seedling transplantation (%)	13.00 ± 0.10	25.00 ± 0.13
Downy mildew (% of infested plants/treatment)	28.00 ± 0.09	48.00 ± 0.13
Alternaria leaf spot (% of plants infested / treatment)	32.00 ± 0.10	54.00 ± 0.14
Insect pests		
Diamondback moth (no. of leaves damaged/ treatment)	7.67 ± 0.28	12.00 ± 0.52
Aphid (% of leaves affected/treatment)	4.73 ± 0.32	12.53 ± 0.28
Tobacco cutworm (no. of plants damaged/ treatment)	12.53 ± 0.31	17.93 ± 0.39
Cabbage butterfly (no. of plants damaged/ treatment)	8.13 ± 0.23	16.40 ± 0.36
Pesticide sprays (no.)	1 ± 0.1	4 ± 0.31
Crop yield (t/ha)	15.78 ± 0.32	13.57 ± 0.21

Table 12.5 Impact of IPM packages in comparison with farmers' practices

Particulars	Treatment 1 (IPM practice)	Treatment 2 (farmers' practice)
Germination percentage	88.2 ± 0.10	83 ± 0.34
Damping off after seedling transplantation (%)	8.00 ± 0.07	17.00 ± 0.07
Red pumpkin beetle (no of leaves damaged per plant)	7.75 ± 0.21	11.15 ± 0.18
Fruit fly population (no of damaged fruits per treatment)	9.75 ± 0.22	12.90 ± 0.27
Downy mildew (% of infested plants/treatment)	42.00 ± 0.10	58.00 ± 0.11
Powdery mildew (no of plant damaged per treatment)	20.00 ± 0.06	34.00 ± 0.10
Pesticide sprays	1 ± 0.23	6 ± 0.15
Crop yield (t/ha)	23.48 ± 0.20	21.36 ± 0.33

with FP. Similarly, insect and disease infestation were found higher in FP than the IPM plot. These results are in accordance with other similar studies (Dinakaran et al. 2013; Rahman et al. 2010).

Cost Benefit Analyses of IPM Packages

Cost benefit analyses provide an important driver and incentive for widespread adoption of IPM technology (Lefebvre et al. 2015). Results of a comprehensive study on three high value vegetable (tomato, cauliflower, cucumber) IPM packages as compared to FP are reported in Table 12.6. The analysis employs gross margin analysis since capital costs are not a significant part of the costs. Reference plot size was 100 m^2. The benefit-cost ratios range between 9 and 24, indicating a high return on cash investments for these technologies. The ratio is much lower for cauliflower because of low prices and the fact that only one head is harvested per plant per production cycle, an important consideration for such small plots. Besides the monetary return, vegetables produced through IPM practices are safe to the soil, environment and human health.

Collaboration to Disseminate IPM Practices and Packages and to Build Local Capacity

In order to disseminate and promote the verified IPM practices and packages, the IPM IL coordinated with USAID value chain programs, government departments, private companies, NGOs, universities and other complementary programs such as

Table 12.6 Cost benefits analysis of tomato, cauliflower and cucumber IPM packages

Description	IPM package	Farmers' practice
Cost of micro irrigation technology US$	23.35	23.35
Total fixed cost US$	24.60	24.60
Seasonal variable cost US$/tomato	18.51	20.17
Seasonal variable cost US$/cauliflower	23.23	18.62
Seasonal variable cost US$/cucumber	32.02	18.46
Seasonal cost US$/tomato	20.06	21.72
Seasonal cost US$/cauliflower	24.78	20.18
Seasonal cost US$/cucumber	33.58	20.02
Seasonal income US$ tomato	218.23	174.58
Seasonal income US$ cauliflower	109.11	90.93
Seasonal income US$ cucumber	305.52	178.22
Seasonal return/profit US$ – tomato	198.16	174.58
Seasonal return/profit US$ – cauliflower	84.33	70.75
Seasonal return/profit US$- cucumber	271.94	158.20
Profitability index (PI)- Tomato	22.09	16.77
Profitability index (PI)- Cauliflower	9.37	8.59
Profitability index (PI) – Cucumber	23.44	16.89
Payback period in years – tomato	0.2	0.2
Payback period in years – cauliflower	0.4	0.5
Payback period in years – cucumber	0.2	0.2
Benefit cost ratio (BCR) – tomato	23.09	17.77
Benefit cost ratio (BCR) – cauliflower	10.37	9.59
Benefit cost ratio (BCR) – cucumber	24.44	17.89

the Market Access and Water Technology for Women (MAWTW) and Initiative for Agriculture Productivity and Commercialization (IAPAC).

IPM Packages/Technology Dissemination Via USAID KISAN Project

In 2013, through an associate award, support for the Nepal IPM IL project was extended to establish a structure to facilitate the technology transfer of verified IPM practices and packages for high-value vegetable crops in the mid-western and far western region in collaboration with USAID's KISAN (Knowledge-based Integrated Sustainable Agriculture and Nutrition) project. KISAN is an important part of the IPM IL technology scaling-up program which is currently working with several thousand farmers in 20 different districts. The IPM IL sites were selected in close coordination with the KISAN team and as such they are in close proximity to where the KISAN project was working. Research results were shared with KISAN for

Fig. 12.1 IPM Demonstration Center- Surkhet, Nepal

extension, and an IPM demonstration center in each district was developed to showcase the verified IPM practices and packages.

The IPM IL through various training activities, field demonstrations (Fig. 12.1), exchange field visits and dissemination of extension materials is facilitating IPM activities into the program. To date, 107 KISAN staff members have been trained in IPM approaches. A report provided by the KISAN team states that 21,004 farmers (Male/Female: 7,461/13,543) have already adopted IPM practices and packages. Farmers are using IPM components such as soil solarization of nurseries, use of *Trichoderma* and *Pseudomonas* as a seed treatment, drenching of the nursery with *Trichoderma* at weekly intervals, use of bio-pesticides, regular inspection of the field, roguing of virus infected plants, use of coco-peat and plastic trays, grafting seedlings, use of nylon nets etc. Additionally, IPM IL has facilitated collaboration between KISAN and Agricare Nepal Pvt. Ltd to extend the supply chain network of bio-products in various KISAN project districts.

Coordination with iDE Projects to Promote IPM Package/Technologies

IPM IL has leveraged a network of observers and educators associated with the existing iDE-managed projects; IAPAC (funded by the European Union) and MAWTW (funded by USAID). The major focus of these projects is to develop small-holder commercial entities around rural collection centers to enable the establishment of a local collection/processing center that provides market access, services, and representation, and enables the private sector to establish local agents that market inputs, equipment and services. These collection centers are in an excellent position to assess the pest situation and make recommendations to members through detailed crop calendars developed in partnership with government extension services and the private sector.

The IAPAC is a 3-year program funded by European Union (EU) implemented in three districts of the mid-western region. iDE is leading the agriculture component of the project and IPM is one of the important aspects of the proposal. IPM IL and IAPAC project are working closely to promote eco-friendly IPM approaches, by training the project staff, facilitating exposure visits and demonstrations, and regularly organizing interaction/sharing meetings. During the year 2014–2015, 2375 farmers (M/F: 508/1867) farmers under the IAPAC project have adopted IPM components in different vegetable crops in the Dang, Rolpa and Banke districts (IAPAC 2015).

Similarly, the MAWTW is a USAID funded project implemented through IDE and SAPROS Nepal as a field implementing partner. IPM IL has actively facilitated extension of IPM technologies through training, demonstrations, exposure visits and other capacity building activities in three districts viz. Kailali, Dadeldhura and Doti. In Dadeldhura, Doti and Kailali districts 5929 farmers (M/F: 1384/4545) were reported to have adopted IPM components in different vegetables crop (MAWTW 2015).

Collaboration with Government Agencies

The IPM IL has continuously worked with the Nepal Agriculture Research Center (NARC) to test and verify IPM components and packages. All IPM packages are approved from a higher level committee (advisory board) chaired by the Deputy Director General with members from NARC and other concerned ministries. Meanwhile, to develop the capacity of local scientists, regular training activities and workshops are co-organized (such as training in disease diagnostics, and bio-pesticides production).

Collaboration with Private Sectors and Developing Community Business Facilitators

Relative weakness of public extension programs is one of the major constraints to IPM adoption (Buckmaster et al. 2014). Some IPM components, especially those that are embedded in products such as resistant varieties, pheromone traps and lures, grafted seedlings, compost, and biocontrol agents can be passed to the private sector as there is a profit incentive to sell them to farmers. Realizing the importance of the private sector in the development and dissemination of sustainable IPM technologies the IPM IL is working with private sector partners such as Agricare Nepal Pvt. Ltd, Gorkha Seeds Company and Bio-technovative Company Pvt. Ltd to develop and strengthen the supply chain for bio products, seed, pheromone traps/lures and nursery materials, and has developed an extension approach that utilizes the network of collection centers established with USAID and government support. The community business facilitator (CBF) model was developed to ensure the regular supply of agricultural inputs including bio-agents at the local level. CBFs collect information about demand for agro-inputs from local farmers and deal directly with district-level agro-input suppliers for timely delivery. CBFs have a formal contract with, and receive commission (8–15 %) from, the input suppliers. Eighty three CBFs were trained and developed by different projects, including 10 by the IPM IL. CBFs are earning an average of NRs 2,900 (US$29) per month, ranging from NRs 2,000 ($20) to NRs 12,500 ($125). Average sales per month are around NRs 25,000 ($250) to 30,000 ($300). On average, a CBF provides his or her services to 55–60 farmers every month. Last year (2014), Agricare sold 21 metric tons of bio-agents (*Trichoderma*, *Pseudomonas*, and *Metarhizium*) worth NRs 6,500,000 ($65,000), which was a 48 % growth increase over their 2013 sales.

Improving Local Capacity Through Training and Workshops

In order to sustain the program efforts and achievements, IPM IL is committed to improve the capacity of local government and private sectors to deliver extension services more effectively in rural areas. In between 2013 and 2015, IPM IL conducted 122 training sessions/workshops and other capacity building events for farmers, government personnel (such as scientists, extension officers), projects (e.g. KISAN), private sectors, NGOs and community based organizations (Fig. 12.2, 12.3, and 12.4). There was a total of 3,726 (M/F: 1,723/2,003) participants. A few of the major events were (a) workshop on seed borne viruses in vegetables (b) international workshop cum training on *Trichoderma* production (c) international workshop cum training on bio-pesticide production (d) virus and disease diagnostic training for early career scientists and, (e) sensitizing workshop on *Tuta absoluta*. Most of these training sessions/workshops were facilitated by experts from various countries and were successful in that participants gained practical knowledge of bio-control agent production and pest diagnosis, particularly addressing its connection to sustainable agriculture as well as environmental protection.

Adoption of IPM Practices and Packages

Assessment of impact of IPM practices and packages on production and productivity revealed that the farmers achieved reduced production costs, increased production and higher economic returns over the conventional farmers' practices

Fig. 12.2 Prof. Naidu leading a training session at NARC, Khajura, Nepal

Fig. 12.3 Prof. Nakkeeran from TNAU conducting the *Trichoderma* workshop in Nepal

Fig. 12.4 (**a–c**) Virus disease survey in a vegetable field in Nepal

Fig. 12.4 (continued)

Table 12.7 Adoption of IPM practices and packages

Project	Households trained on IPM (no.)	Households adopting IPM practices/packages (no.)	Adoption (%)
IPM IL	1,223	1,002	82
KISAN	49,990	20,996	42
MAWTW	10,000	2,900	29
IAPAC	4,000	1,080	27
Total	65,213	25,978	40 (avg.)

(Table 12.7). Although some of the progressive farmers adopted entire packages, few major components of the packages e.g. selection of seeds/seedlings, use of bio-control agents (such as *Trichoderma*, *Pseudomonas*), nursery netting materials, use of coco-peat and plastic trays, tomato grafting, use of pheromone traps, and use of neem-based pesticides were adopted by a large number of farmers. More than 80 % of the farmers under IPM IL, 42 % in KISAN project, 29% in MAWTW and 27 % in IAPAC project have been recorded to have already adopted some form of IPM practices and packages for vegetable production (Table 12.7). Meanwhile, it is important to note that IPM IL support to KISAN is currently in its 2nd year, whereas it is just year 1 for the MAWTW and IAPAC project.

Future Thrusts

Efforts to further expand and popularize these IPM technologies in vegetable growing areas in Nepal are currently in progress. A formal agreement has been made with the USAID funded 'Promoting Agriculture, Health and Alternative Livelihoods' (PAHAL) and the DFID funded 'Building Reliance and Adaptation to Climate Extremes and Disasters' (BRACED) project to further expand and diffuse the verified IPM practices and packages. These two projects are proposed to reach to about 300,000 households. The IPM IL will train the project staff and assist in setting up demonstration plots. Similarly, as the vegetable packages were approved by an advisory body chaired by the Deputy Director General (DDG) from the Department of Agriculture (DoA), an effort has been made to streamline the IPM practices and packages into the government system. Using mass media and mobile phones are also a part of the 'scaling-up' strategy. As a pilot program the IPM IL has already started using the bulk SMS system to warn farmers/villages of impending pest infestations and to provide communication among villages to allow early pest management interventions.

Lessons Learned and Recommendations

In general, as a majority of farmers are uneducated and are uninformed about current improved practices of farming, an increase in educational training and awareness of IPM techniques and adoption is warranted. Promotion of alternative approaches to pesticides such as IPM, which can be simple, cheap, environmentally sound and locally available to resource poor farmers, need to be the focus of educational programs (Dasgupta et al. 2010). To increase IPM practices, developing programs that will assist growers in the transition could be one of the strategies (Goldberger et al. 2013).

IPM packages that are dynamic and need-based approaches are very important in the current context of a rapidly changing pest complex in the spatial and temporal scale and diverse methods of cultivation. However to match the complexity of IPM messages, it is important to develop and evaluate multi-faceted and dynamic efforts to integrate locally-adapted, farmer friendly, conventional and biorational methods of pest management (Ricker-Gilbert et al. 2008).

Integrated, continuous and multi-location research should be prioritized by national research organizations, such as NARC and agriculture universities. Current barriers to this approach include a weak extension system, lack of organizational set-up, lack of co-ordination among research and extension organizations and very few and often inadequately trained extension agents in Nepal (Paudel et al. 2013). Development of effective extension policies and a mechanism to integrate various players in extension functions in addition to governmental extension, such as industry, private consultants, NGOs, universities, farmers' associations, research institutes, and others will be a key.

The public sector is generally over-burdened (Roth 1987) and therefore building and promoting profitable and vibrant private sector supply chains of pest management inputs is important. Supply chains that are able to supply pest control technologies, seeds and other agricultural inputs to the farming communities need to be developed and strengthened. It is very important to assure that these inputs and supplies are available in the right quality, at the right time, and in the right place for farmers to access what is needed at a reasonable price.

Correct identification and diagnosis of insect pests is the first step in the IPM approach and leads to the implementation of prophylactic or remedial measures (Miller et al. 2009). However, diagnostic capacity is poorly developed to nonexistent and therefore building capacity of local scientists and extension officers will be a key. Improving lab facilities and training field technicians in the diagnosis of plant diseases, insects and mites, and developing an operational system for identification and diagnosis is very important. This will not only directly benefit farmers but will also help to reduce the risk of accidental introduction of new pathogens/insects into the country.

In Nepal all pesticides are imported and in the absence of proper pesticide regulations and policies, farmers continue to be exposed to high health risks (Dhital et al. 2015). Increasing pesticide use is not being accompanied by a similar increase in regulatory policies designed to protect people and the environment from risks. The government should consider the development of registration of traders and small sales kiosks and regulatory policies for the importation of products and standards for packaging and labeling, coupled with a strong mechanism for monitoring and enforcement.

The role of mobile communications technology is increasingly allowing information to be shared in real time, linking small sales kiosks and cooperatives to local, national, and international business and markets in ways that have not previously been possible. These tools allow farmers to make better planting decisions, reducing postharvest losses and crop damage due to insect pests and weather while increasing access to markets. Wherever it is affordable and applicable, mobile technology should be used to improve communication and simplify logistics (Tuttle 2012).

Gender influences knowledge acquisition and on-farm decisions (Erbaugh et al. 2003; Rubin et al. 2009). Women farmers are generally responsible for pest management activities, however the majority of research and development programs have rarely addressed their specific needs (Malena 1994). Therefore, IPM programs must take into account the gender-related, socioeconomic factors that influence the creation, adoption and effective implementation of IPM technologies.

The promotion of IPM practices and packages requires a whole set of factors beyond pest control. Proper certification of IPM produced vegetables is one of the major factors (Esser et al. 2012). There are some difficulties for a country like Nepal to guarantee and certify IPM grown produce due to a lack of expert knowledge in production and certification. Therefore, one of the possible approaches should be to promote IPM-based production and group certification by farmer groups, which can be done by advocacy, marketing and channeling of commodities to the market.

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Chapter 13
IPM Vegetable Systems in Uganda

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Abstract Smallholder famers in Sub-Saharan Africa (SSA) have been encouraged to produce horticultural crops as an agricultural and rural development strategy to enhance incomes and improve household nutrition. In Uganda, intensified production of marketed vegetable crops has led to changing agricultural practices, including crop and input-intensification, a changing set of pests, and increased use and reliance on synthetic pesticides to manage these pests. Beginning in 2002, the IPM CRSP team in Uganda implemented a participatory IPM program with smallholder farmers to develop and disseminate alternative pest management strategies for managing priority pests and reducing pesticide usage on tomato. The major pest constraints addressed were late blight, bacterial wilt, viruses, bollworm, aphids, thrips and white flies. Baseline farmer surveys indicated that farmers were spraying a variety of pesticides 12–24 times per growing season. The component technologies developed into a package and disseminated to farmers included a bacteria wilt resistant tomato variety MT56, mulching, staking, and a minimum spray schedule of 3–4 pesticide sprays per season. Impact assessments indicated that yields were 40 % higher when the package was used and reduced production costs (by reducing the number of sprays) that led to higher net revenues for IPM-practicing tomato farmers. Use of MT56 and mulching led to a 21 % reduction in production costs and led to an internal rate of return of 250 % if adopted. Use of tomato variety MT56 reduced production cost by 21 % with a Benefit: Cost ratio of 770. Other IPM technologies developed included grafting using bacterial wilt resistant rootstocks; seedling production using low tunnel systems for pest/vector exclusion; and good nursery management practices.

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Introduction

Over the past two decades, smallholder famers in Sub-Saharan Africa (SSA) have been encouraged to produce horticultural crops to enhance incomes and improve household nutrition (Delgado et al. 1998; Doward et al. 2004; Weinberger and Lumpkin 2005; World Bank 2007). The demand for horticultural produce is being driven by urbanization, increasing incomes, exports and a growing awareness of the nutritional benefits of such crops (World Bank 2007). Vegetables are an important source of many essential micronutrients including vitamins A, C and K, folate, thiamine, carotenes, several minerals, and dietary fiber. This is especially pertinent for SSA where one-third of preschool children suffer from vitamin A deficiency (WHO 2007). Increased demand has led to increased employment opportunities through expansion of value chain suppliers and increased agro-processing and marketing of processed foods. Thus, diversifying smallholder production systems into horticultural production has been advocated as an agricultural and rural development strategy in sub-Saharan Africa.

The emphasis by many governments and foreign donors in East Africa (EA) on intensifying the production of marketed vegetable crops for domestic, regional and international markets has led to changing agricultural practices, including input-intensification, that have induced a changing set of pests leading to increased losses, and a resultant increase in the use of synthetic pesticides. In turn, increased pesticide usage has led to pest resistance and resurgence, increased cost of production, food safety and human health concerns, and a decline in bio-diversity (Puz-y-Mino et al. 2002; Matthews et al. 2003; Ntow et al. 2006; Ngowi et al. 2007). Horticultural production worldwide accounts for 28 % of global pesticide use (World Bank 2007). This has created a strong demand for IPM research and the development of alternative management strategies that are less reliant on synthetic pesticides.

In Uganda, land under vegetable production increased by 30 % during the period of 1993–2003 (Ssonko et al. 2005). Among the main vegetable production constraints are insect pests and diseases and most producers of these crops rely on synthetic pesticides as their primary method of pest control. Pesticide use has increased in Uganda because pesticides are perceived to be effective in protecting higher value crops and alternative pest management practices are unavailable. Past agricultural research efforts largely focused on pesticide efficacy trials and ignored the development of pest management alternatives (IPM CRSP 2007; Karungi et al. 2011). However, there are growing concerns regarding pesticide usage including pest resistance, increased production costs, and negative impacts on human health and the environment. For vegetable production in Uganda to be sustainable, the IPM

CRSP engaged in an integrated pest management research program to develop safer and more effective pest management alternatives that reduce or supplant the use of synthetic pesticides and maintain high productivity levels.

Integrated pest management (IPM) is promoted as an alternative to sole reliance on chemical pesticides. Its primary goal is to manage destructive pest populations using a variety of practices including pest monitoring, biological controls, host plant resistance and cultural practices while attempting to reduce or eliminate the use of chemical pesticides. These component practices are then combined to form a pest management system. It is considered to be a cost effective, environmentally friendly and appropriate technology for small holder African producers.

Except in cases of higher value export crops, for example cotton, many attempts to implement IPM in developing countries over the past three decades have met with limited success (World Bank 2007; Orr 2003; Morse and Buhler 1997). A variety of policy, research and socioeconomic factors are acknowledged to have constrained IPM adoption. Others have indicated that the central problem is one of transferring IPM knowledge and systems to farmers (Erbaugh et al. 2007; Rajotte et al. 2005; World Bank 2007; Dent 1995). Increasing farmer participation in the development and implementation of IPM programs emerged as a strategy for increasing the relevance and adoption of IPM, particularly among smallholder farmers (Erbaugh et al. 2002; Yudelman et al. 1998).

Prioritizing Tomato and Developing an IPM Research Strategy

The IPM CRSP (Collaborative Research Support Program, currently known as IPM Innovation Lab) began implementing a participatory IPM program with tomato growers in Uganda in 2002. Tomato was selected as a focal crop for project activities because it was the most highly ranked horticultural crop in a 2006 regional survey of crop priorities conducted by the Association for Strengthening Agricultural Research in Eastern and Central Africa (ASARECA) and because it met two other important project criteria. First, tomato is an important commercial (cash) crop that is grown predominately by small scale producers (2 ha.) including women for home consumption and domestic markets (Mwaule 1995; Mukiibi 2001; Kasenge et al. 2002; Ssonko et al. 2005). Second, baseline assessments of small scale producers in Uganda found tomato production to be associated with the excessive use of synthetic pesticides with producers commonly reporting the application of pesticides 12–24 times per season (Akemo et al. 2000). These same assessments indicated that farmers were unaware of alternative means of managing pests and thus were totally reliant on synthetic pesticides as their sole means of pest control.

Participation, as an agricultural development strategy, emerged in recognition that traditional top-down technology development and transfer programs were having only limited impacts at the farm level. Involving farmers in the research process, through their participation, was advocated as a method to adapt and improve the appropriateness and adoption of agricultural technologies. An objective of farmer participation in agricultural research, or what is known as (PAR), is to work with farmers to develop appropriate agricultural technologies to meet their production needs. This objective was particularly relevant to the IPM CRSP program in Uganda because farmer knowledge of pests and pest management alternatives to synthetic pesticides were lacking. Increasing farmer participation in the IPM CRSP program through their engagement in each step of the research process, from problem identification to on-farm trials, emerged as an important strategy for increasing the relevance and use of IPM, particularly among small-scale tomato growers in Uganda. This approach was called participatory IPM (PIPM) by the IPM CRSP.

Two objectives guided our PIPM approach: First, was to work with farmers to develop appropriate agricultural technologies to meet their production needs. This objective was particularly relevant to IPM programs in Uganda because effective pest management alternatives to synthetic pesticides were not available – or on the shelf. A second objective emerged as important in our work with small scale farmers, and that was to raise their knowledge and understanding of biological factors and ecological interactions, so as to improve their capacity to manage pests and diseases and to produce a healthy crop. Since both objectives require information and knowledge sharing among farmers, scientists and extension agents to be effective, our IPM program came to be increasingly linked to participatory research and extension approaches.

Establishing Tomato Priorities

The initial farmer and biological baseline assessments (see Table 13.1) conducted by the IPM CRSP and other development partners established that low tomato yields were mainly attributable to the high incidence of pests and diseases, lack of improved varieties, and growers lacking knowledge of alternative pest management practices and good agricultural practices for growing tomato (Mwaule 1995; Akemo et al. 2001; Kagezi et al. 2001; Ssonko et al. 2005; Ssekyewa 2006; Table 13.1). The baseline assessments established that the most important diseases and arthropod pests were Late and Early blights (*Phytophthora infestans* and *Alternaria solani*); bacterial wilt (*Ralstonia solanacearum*); root knot nematodes (*Meloidogyne* spp.); African bollworm (*Helicoverpa armigera*); thrips (*Thrips* spp. and *Frankliniella* spp.); whitefly (*Bemisia tabaci*); aphids (*Aphis* spp. and *Myzus persicae*); and mites (*Polyphagotarsonemus latus* and *Tetranychus* spp.) (Mwaule 1995; Akemo et al. 2001; Kagezi et al. 2001; Ssonko et al. 2005). Later country surveys determined that the most prevalent tomato viruses were *Tomato mosaic virus* (*ToMV*), *Tobacco mosaic virus* (*TMV*), *Cucumber mosaic virus* (*CMV*), *Tomato yellow leaf curl virus* (*TYLCV*) and potyviruses with incidences in farmers' tomato fields ranging between 11 % and 88 % (Ssekyewa 2006; Arinaitwe 2013).

Table 13.1 Farmers reports of tomato production constraints in Central Uganda

Problem	Local name	% of farmers reporting problem
Blight	Kubabuka	100
Wilting	Okuwotoka	100
Mixing pesticides	Okutabula eddagala	100
Blossom end rot	Okuvunda muntobo	80
Correct spraying methods	Enfuyira entuufu	60
Insect pests e.g. boll worm	Obusaanyi, etc.	100
Cutworms and crickets	Akawuka akassala obuboga obuto- kasanyi	100
Flower abortion	Ebimuli bikunkumuka	80
Thrips	Obuwuka obudugavu nga butono	80
Stunting, leaf distortion, curling, crinkling, mosaic	Okugengewala	60
Expensive sprayers	Ebbomba tezigulika	80
Poor market prices	Katale kafu	100
Purely vegetative tomato growth	Temulisa	100

Source: Akemo et al. (2000)

The IPM CRSP farmer baseline assessment conducted in the central region districts of Wakiso and Mpigi determined that the predominant management practice used by tomato growers to control the pests and diseases was synthetic pesticides (Akemo et al. 2000). A wide range of pesticides was identified with the most commonly mentioned being Permethrin (Ambush©), Fenitrothion (Sumithion©), Dimethoate, Nurelle-D© (combination of Cypermethrin and Chlorpyrifos), Cypermethrin (Sherpa©), Chlorpyrifos (Dursban©), Dithane M45 (Mancozeb©), Metalaxyl, and Ridomil© (Mancozeb + Metalaxyl) and the herbicides Salute (Trifluralin) and Zancor (Metribuzine) (Akemo et al. 2000). Very few farmers used herbicides, with most indicating that they weeded by hand or used hoes, depending on the growth stage of the plant. Fungicides were the most commonly used pesticides because fungal blights, especially late blight (*P. infestans*), were prevalent and if left unsprayed resulted in crop losses greater than 75 % (Akemo et al. 2000). Farmers' indicated that they routinely sprayed fungicides with the majority spraying as often as twice per week throughout the tomato growing season. Some farmers also indicated that they used fungicides to control bacterial wilt although there is no known chemical control yet available for this disease. Pesticides were commonly mixed in backpack sprayers by hand and the practice of mixing several pesticides together into a "cocktail" was common. Additionally, the majority of the farmers was unable to read pesticide labels and application rates were arbitrarily measured using table spoons and bottle tops (Akemo et al. 2000). Only a few farmers used specialized protective clothing while spraying.

Farmers were only vaguely familiar with health problems related to pesticide exposure with a few mentioning nausea following spraying and several women indicating that men do the spraying because it was unhealthy for pregnant women to do so. Farmers' were generally unaware of the long-term health risks from exposure to pesticides including the potential for cancer development and endocrine disruption resulting from exposure to fungicides containing mancozeb (Novikova et al. 2003). The dithiocarbamate family of fungicides is also suspected to have reproductive (Restrepo et al. 1990) and mutagenic effects in human cells (Puz-y-Mino et al. 2002). The farmer practice of excessive, unsafe use of pesticides eventually led the IPM CRSP team to develop a short field-based course for farmers on safe and correct pesticide usage and safety. This course was provided four times in Uganda and then was taken and used with growers in Kenya and Tanzania.

Developing Components of an IPM Package for Tomato

From 2002 to 2014, the IPM CRSP (IL) team in Uganda developed and disseminated alternative pest management options for managing priority pests and reducing pesticide usage on tomato. The IPM package for tomato that was eventually developed consisted of nursery management practices (soil sterilization), a bacterial will resistant tomato variety MT56, mulching, staking and three sprays per season.

Bacterial wilt (*Ralstonia solanacearum*) was the most important and consistent pest constraint on tomato causing up to 100 % crop loss in some areas of Uganda. It is perpetuated in the soil and can be carried from one field to another on shoes, farm implements or vehicles and through irrigation and surface water. Management of *R. solanacearum* is difficult owing to its wide host range, the latency of the pathogen and lack of chemical controls. There are no chemicals known to be effective against the disease. Most of the commercially grown cultivars in Uganda such as Roma, Marglobe, Heinz, Moneymaker, Onyx and local Nganda were highly susceptible (Akemo et al. 2001). As a result, control strategies for *R. solanacearum* relied on manipulating cultural practices and host plant resistance. One novel approach investigated by the IPM CRSP was grafting susceptible, yet market preferred tomato lines, onto resistant root stocks.

Resistant Varieties

The search for resistant germplasm focused on the bacterial wilt disease caused by *R. solanacearum*. In 1987, a research program on tomatoes was initiated at Makerere University with a view of developing tomato varieties that would be high yielding and well adapted to various ecological conditions of Uganda. Twenty three introduced tomato cultivars formed the foundation of the research. MT56 was one of introduced cultivars. It was brought in from the Ohio Agricultural Research Development Center (OARDC) Tomato Breeding Program in the USA. MT56 and MT55 proved to be among the cultivars with the greatest potential in terms of yield parameters and resistance to *R. solanacearum* (Rubaihayo and Rusoke 1992). As a result of their performance, MT55 and MT56 formed the basis for future work by the IPM CRSP. In 1999, in an on-farm trial laid out in a RCBD with four replications, MT55, MT56, Redlander (from Australia), and a local tomato as a control were evaluated. Results from participatory trial evaluations with farmers indicated that they preferred MT56 because of its heavy flowering and fruit setting (Akemo et al. 2000).

Confirming the Performance of MT56 in Different Agro Ecological Zones in Uganda

Over a 10 year period, research conducted in Uganda by the IPM IL continued to demonstrate the performance of MT 56 and its superior resistance to *R. solanacearum*. In 2010, the IPM IL in Uganda set out to confirm the performance (adaptability, stability and survival) of MT56 for a release application as a commercial tomato variety. A randomized complete block design (RCBD) was used to set up multi-location trials with five tomato genotypes (MT56 vs. four commercial varieties grown in the country: Tenjeru, Marglobe, Moneymaker and Roma) and replicated three times in six different agro-ecological areas of Uganda. The results from the multi-locational trials showed that MT56 was consistent in resistance to bacterial wilt and the best performer in terms of yield and survival among the genotypes and was stable across all sites evaluated (Fig. 13.1; Asiimwe et al. 2013). The trials confirmed and verified MT56 resistance to *R. solanacearum* in different locations in the country. This information, and required verifications including the validation of performance in different seasons and different agroecological zones; and compilation of genetic background and variety description were submitted to the Ugandan National Varietal Release Committee in 2012. MT56 has made a great impact in the central region of Uganda (New Vision daily paper, March 6, 2012).

Grafting

Another option for managing bacterial wilt developed by The IPM CRSP Uganda team was grafting susceptible tomato lines onto resistant root stocks. This practice had been applied extensively in Asia, but was relatively new to the East Africa region (Matsuzoe et al. 1990; Ibrahim et al. 2001; Black et al. 2003). In Uganda, this work began with on-station field trials to assess the performance of bacterial wilt susceptible tomato grafted onto three indigenous solanaceous (*Solanum* spp.) rootstocks (Magambo et al. 2003). The indigenous rootstocks used were *Solanum complycanthum* (locally known as Kitengotengo), *Solanum indicum* (Katunkuma) and *Solanum* sp. (Katengotengo). ‘Onyx’, a susceptible commercial variety was used as the scion. Ungrafted ‘MT 56’ and ‘Onyx’ were included as bacterial wilt resistant and susceptible checks, respectively. A randomized complete block design was used with three replicates. Data was collected on pest and disease incidence, growth and yield parameters from ten plants per plot.

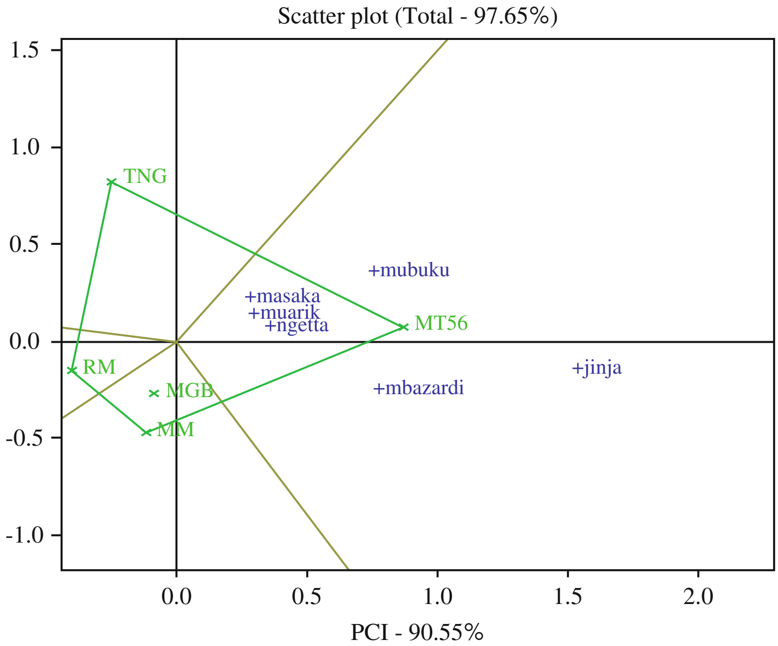

Fig. 13.1 A scatter GGE biplot for tomato yield (kg/ha) obtained from the five evaluated genotypes across the six evaluation sites (Where: *MGB* Marglobe, *TNG* Tengeru-97, *RM* Roma, *MM* money maker; Locations (districts): mbazardi = Mbarara, Ngetta = Lira, muarik = Wakiso, mubuku = Kasese, Masaka and Jinja) (Source: Asiimwe et al. 2013)

All rootstocks united readily with the tomato variety although an overgrowth occurred at and above the graft union, indicating higher growth rate and/or vigor of Onyx compared to that of the rootstocks. Results indicated that grafting significantly affected the incidence of *R. solanacearum* on tomatoes (Fig. 13.2). Bacterial wilt incidence was highest on un-grafted Onyx, the susceptible tomato variety, followed by Onyx grafted on *S. indicum* root stock. The lowest incidence was on Onyx grafted on Kitengotengo, although this was not significantly different from that of tomato variety MT 56 and Katengotengo. Additionally, fruit yield per plant was significantly different for the different treatments (Fig. 13.3). The highest fruit yield and was recorded on MT56 plants while the lowest was on ungrafted Onyx. All ungrafted Onyx plants were destroyed by *R. solanacearum* in the early stages of growth and therefore did not produce any fruit. Tomato variety MT 56 produced the highest yield of 2.84 kg/plant, which was more than three times ($P>0.05$) higher than that of the grafted plants.

These results indicated that although the indigenous solanaceous rootstocks, *Kitengotengo* and *Katengotengo* conferred bacterial wilt resistance to the commercial tomato variety through grafting, they appeared to have a negative effect on tomato yields. The recommendation was that grafting using these indigenous solanaceous rootstocks was an economically viable IPM practice for areas where soils were infested with bacterial wilt disease, and bacterial wilt tolerant or resistant tomatoes were not readily available.

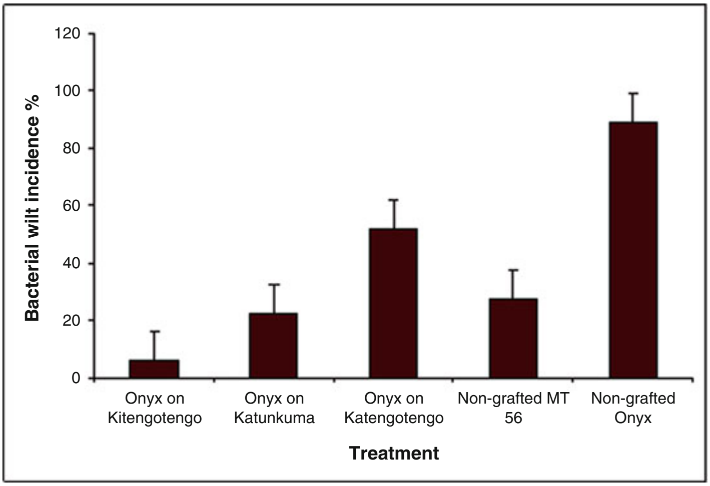

Fig. 13.2 Effect of grafting on incidence of bacterial wilt on tomato (Source: Ssonko et al. 2011)

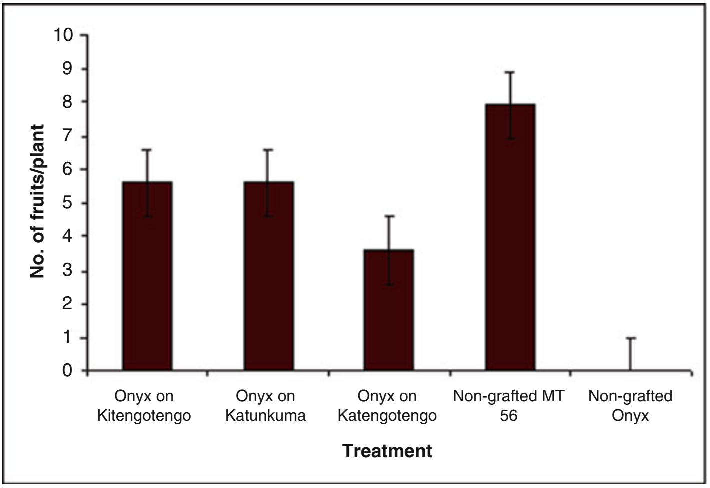

Fig. 13.3 Effect of grafting on tomato yield (Source: Ssonko et al. 2011)

Later grafting efforts focused on using MT56 as rootstock for popular but highly susceptible tomato varieties in the country. In a study, five treatments: Heinz 1370 VF, Money Maker, Marglobe, and Tanya were grafted onto MT56 and along with non-grafted MT 56 used in a randomized complete block design with three replications. Results indicated that MT56 made strong unions with other tomato varieties. Results on fruit yield indicated that the mean weight per fruit of tomatoes varied significantly among the treatments (Fig. 13.4). Un-grafted-MT 56 had the highest weight per fruit compared to the other tomato varieties grafted on MT 56 (Ekepu 2013).

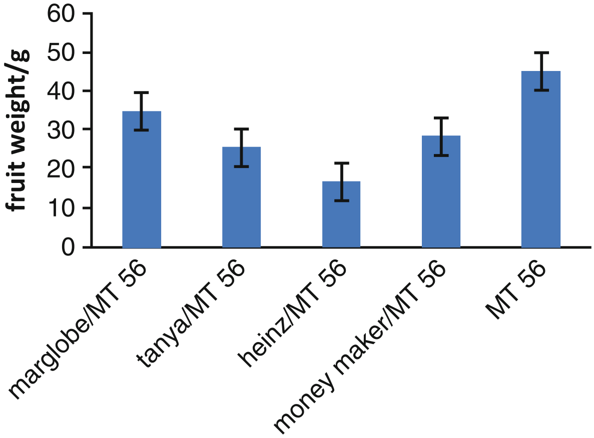

Fig. 13.4 Effectiveness of grafting tomato-on-tomato

MT 56 was later transferred to the Kenya IPM IL site and used as a bacterial wilt resistant rootstock for grafting onto commercially preferred varieties because the fruit shape of MT 56 was less preferred in Kenyan markets. Grafting trials with MT 56 in Kenya again indicated that grafting significantly reduced the incidence of *R. solanacearum* and increased fruit yield. This has resulted in the variety being widely disseminated in Kenya as a rootstock and the emergence of small entrepreneurs who specialize in producing the grafted seedlings.

Cultural Practices

Mulching and staking of tomato were introduced as cultural practices to reduce mechanical disease transmission, suppress weeds, modify soil temperature and conserve moisture. For these reasons, mulching is considered to be a good agricultural practice. Mulching is less well known as a soil borne disease prevention practice. Mulching around tomato plants can prevent the transmission of fungal and bacterial pathogens by reducing the impact of rain drops and the concomitant splashing of disease spores and bacterium onto plants. This is important because major fungal diseases affecting tomato in Uganda including Late and Early blights (*P. infestans* and *A. solani*), and Fusarium wilt (*Fusarium oxysporum* f. sp. *lycopersici*) have spores that form on the surface of leaves and can be transmitted by wind or rain. Infected plant material can serve as a future source of inoculum and remain in the soil for long periods of time.

Beginning in 2005, a series of on-station and on-farm trials were conducted to assess the effects of cultural practices in managing insect pests and diseases. The cultural components were first assessed individually and then later trials combined these components. The individual treatments were: (i) mulching (using straw mulch), (ii) staking tomato plants, and (iii) untreated tomato plants as a check. MT 56 was the tomato variety used in the study. The treatments were arranged in a randomized complete block design with three replications.

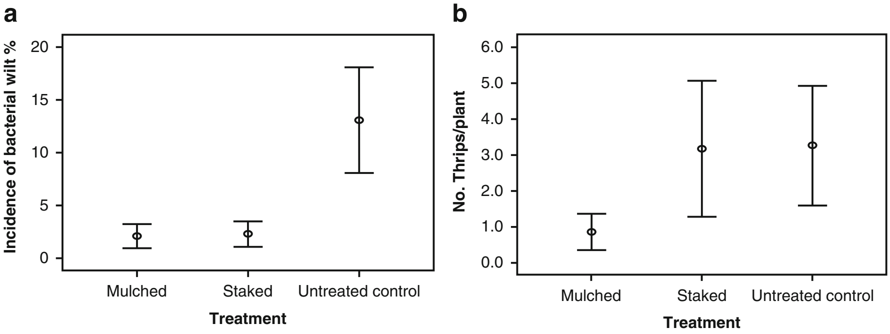

Fig. 13.5 (**a**) Incidence of bacterial wilt on tomato in the different treatments over three seasons. (**b**) Occurrence of thrips on tomato in the on-farm treatments

Results from three rounds of on-station trials indicated that bacterial wilt and fruit yield were significantly affected by treatments ($P<0.05$). Mulching and staking of tomato plants greatly reduced incidence of bacterial wilt on tomato, when compared with the untreated plants (Fig. 13.5a). Mulched plants gave the highest fruit yield followed by staked plants and the untreated plants yielded the least. Results from on-farm validation trials indicated that the treatments significantly affected thrips population ($P<0.05$). Thrips populations were lowest on mulched plants and highest on untreated plants though populations on the latter were not significantly different from those of staked plants (Fig. 13.5b). Mulching also reduced the occurrence of weeds; reduced irrigation frequency from three to one watering per week; reduced the incidence of soil borne fungal diseases and was associated with reduced use of fungicides.

Tomato Viruses and Low-Tunnel Systems for Virus Disease Management

A field survey was conducted to assess the incidence and severity of viral diseases in tomato fields in eight major growing districts in Uganda (Arinaitwe et al. 2013). The most frequently found viral diseases were *Tomato mosaic virus (ToMV), Tobacco mosaic virus (TMV)*, *Cucumber mosaic virus (CMV)*, Potyviruses and *Tomato yellow leaf curl virus (TYLCV)*. Results showed that about 15 % of the surveyed fields had a virus disease incidence of >90 %.

The IPM IL team conducted trials to evaluate the effect of row covers and screen house seedling production on whitefly infestation and transmission of *TYLCV*. The incidence of viral diseases in Uganda is attributed to the prevalence of insect vectors, notably aphids (*CMV*) and the white fly (*TYLCV*). Insect barrier row covers (= low tunnels) have been shown to successfully reduce whitefly population levels, and reduce or delay the incidence of whitefly transmitted viruses (Natwick and Durazo 1985; Karungi et al. 2013). Studies on tomato (Abaasa 2010; Jurua et al. 2014) in

Uganda showed that insect proof row covers used in the nursery and in the field can greatly reduce insect vector and virus disease incidence. Results over two growing seasons in 2013 showed that for the duration of the application, insect proof plastic row covers kept aphids and white flies off the protected plants and reduced the occurrence of vectors. Also, the row covers significantly reduced incidence and severity of *Cucumber mosaic virus (CMV)* and *Tomato yellow leaf curl virus (TYLCV).*

In Kenya seedlings produced in a screen house and then transplanted to the field were compared to seedlings produced in unprotected nurseries. The screen house seedlings were generally more vigorous, had lower whitefly infestations and lower incidences of virus. The highest yield (34 t/ha) was recorded from the seedlings raised in the screen house. The lowest yields were recorded for seedlings produced in unprotected nurseries (20 t/ha).

Reduced Pesticide Applications

In order to reduce the number of spray applications on-station trials were conducted to assess the effect of different spray schedules on pest/disease incidence and crop yield. The experiment used a randomized complete block design with six treatments that were replicated four times. The treatments were: (**T1**) spraying once every week with a mixture of Dimethoate and Agrolaxyl chemicals to control both insect pests and disease, (**T2**) spraying the mixture once in vegetative growth and once during flowering, (**T3**) spraying the mixture twice during flowering and twice during fruiting, (**T4**) weekly application of Agrolaxyl fungicide sprays only, (**T5**) weekly application of Dimethoate insecticide only, and (**T6**) untreated/unmulched. Results on fruit yield and cost-effectiveness of the different spray schedules indicated the most profitable spray schedule was where two sprays of the mixture of the fungicide and insecticide were applied once in vegetative and flowering stages. Weekly sprays with the fungicides brought negative returns (Table 13.2).

Table 13.2 Mean yields of marketable tomatoes and marginal returns for the different pesticide spray schedules

Treatment	Yield Kg/ha	Yield gain over control Kg/ha	Gross returns* (Ug.Sh/ha)	Cost of sprays (Ug.Sh/ha)	Net returns* (Ug.Sh/ha)
T1	1343	869	1,738,000	1,252,571	485,429
T2	1240	766	1,532,000	313,143	1,218,857
T3	1261	787	1,574,000	776,286	797,714
T4	1026	552	1,104,000	1,200,000	−960,000
T5	1100	626	1,252,000	52,571	1,199,429
T6	474	–	948,000	–	–
L.S.D	529.9	–	–	–	–

*Market price of tomatoes was 2000/= per kilogram; In calculating net returns other input costs were kept constant apart from costs associated with pesticide (chemical) usage (Source: Tumwesigye 2012)

Participatory Field Assessment of Tomato IPM Components

For two consecutive seasons in 2013 (A and B), the Kiwenda Tomato Growers Association hosted the tomato IPM modified Farmer Field School (FFS) in Wakiso district. The IPM treatments tested by the school combined component technologies at different levels including: (**1**) Staking+mulching+3 sprays a season+MT56 tomato variety; (**2**) Mulching+3 sprays a season+MT56; (**3**) Weekly sprays+MT56; (**4**) Mulch+MT56 and (**5**) MT56 only (control). The sprays were a fungicide (Agrolaxyl) and an insecticide (Dimethoate). The treatments were set up in randomised block design with three replications. These were set up in 5×5 m plots. The plants were planted at a spacing of 60×45 cm. Data was collected to establish the effect of the packages on insect pest and disease occurrence and severity, and on yield. Results indicated that the IPM packages significantly affected occurrence of aphids, white flies and leaf miners as well the severity of late blight and viral diseases on tomato (Table 13.3). Marketable yield was also significantly affected by the treatments with IPM technologies significantly increasing fruit yields over the untreated; and yielding comparably or sometimes even higher than the weekly sprayed plots (Table 13.4).

Impact Assessment of Tomato IPM Activities in Uganda and East Africa

In Uganda, the major constraints addressed were late blight, bacterial wilt, viruses, bollworm, aphids and white flies. Baseline farmer surveys had indicated that farmers were spraying a variety of pesticides 12–24 times per growing season. The technologies developed into a package and disseminated to farmers included a bacterial

Table 13.3 F statistics for the combined analysis of the effect of IPM technologies and sampling date on insect pest infestation and disease severity on tomato at the Kiwenda FFS

	F statistics					
Source	d.f	Aphids/ plant	Whiteflies/ plant	Leafminers/ plant	Late Blight severity	Viral disease severity
Treatment	4579	4.549***	26.810***	5.516***	13.001***	6.316***
Sampling date	3579	1.362	14.153***	4.650**	161.278***	27.438***
Treatment × Sampling date	12,579	3.673***	3.826***	1.373	6.689***	3.001***

Values with asterisks indicate significance: ***0.001; **0.01; *0.05; whereas values without asterisks indicate no significance

Table 13.4 Effect of IPM treatments on yield (number of fruits per plant) at the Kiwenda FFS in 2013

Treatment	2013A	2013B
Staking+mulching+3 sprays a season+MT56 tomato variety	8.70 a	19.40 a
Mulching+3 sprays a season+MT56	7.93 a	19.07 a
Weekly sprays+MT56	9.67 a	10.63 b
Mulch+MT56	8.10 a	4.53 c
MT56 only (control)	4.23 b	2.43 c
Mean	7.73	11.21
LSD	2.934	3.091
P-Value	0.005	<0.001

Means in a column followed by the same letter are not significantly different at $P < 0.05$

wilt resistant tomato variety MT56, mulching, staking, and a minimum spray schedule of 3–4 pesticide sprays per season. Impact assessments indicated that yields were 40 % higher when the package was used and reduced production costs (by reducing the number of sprays) that led to higher net revenues for IPM-practicing tomato farmers. Use of MT56 and mulching led to a 21 % reduction in production costs and led to an internal rate of return of 250 % if adopted. Use of tomato variety MT56 reduced production cost by 21 % with a Benefit: Cost ratio of 770 (IPM IL 2014).

Based on the reduced number of sprays (from 12 per season to 3), profitability was increased by $500 per hectare for tomato producers. A rough estimate of the extent of tomato production in the agro-ecological zones where trials were conducted is 2000 ha. Given the cost savings from reduced spraying, the potential increase in profits is $1 million if all the farmers in the agro-ecological zone adopted the IPM practices. In addition to these potential benefits it is expected that the benefits from reduced human exposure to pesticides and their adverse health impacts, as well as reduced environmental impacts would be substantial.

Economic surplus modeling was used to estimate benefits from adoption of six IPM technologies developed by the IPM IL project in East Africa to improve tomato production. Results indicate that IPM adoption results in yield increases ranging from 54 to 268 % depending on the adopted technology. IPM technologies reduced costs ranging from 70 % (in the case of grafting and high tunnels in Kenya) to about 6 % (mulching in Uganda). The study shows that the internal rates of return for six technologies exceeded the market interest rate implying that all were worthwhile interventions with positive net present values that ranged from $820,000 onwards. Summing over the six interventions, the aggregate undiscounted impacts each computed over a 20-year period amount to $526 million achievable between 1994 and 2014 (IPM IL 2014).

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Chapter 14
Impacts of IPM on Vegetable Production in the Tropics

George W. Norton, Jeffrey Alwang, and Majdeddin Sayed Issa

Abstract Integrated pest management (IPM) seeks to manage pests in an economically efficient and environmentally sound manner. Given the multiplicity of IPM practices on tropical vegetables, and the diversity and levels of impacts, no one method is suitable for all IPM impact assessments. Due, in part, to the cost of rigorous assessment, IPM impact studies have been selective in the programs and practices targeted for evaluation and have varied in their depth. This chapter provides a summary of economic and environmental impact assessments of IPM on tropical vegetables. It focuses primarily, but not exclusively, on studies completed on the IPM CRSP (IL). Methods for measuring IPM impacts are briefly reviewed, followed by results of empirical studies. Finally lessons are drawn for IPM programs and for IPM impact assessment. The total estimated impacts of IPM on tropical vegetables exceed $500 million for just the small set of careful empirical evaluations that have been completed, making tropical vegetable IPM research and extension a highly-profitable public investment.

Keywords **IPM** Impact assessment • Tropical vegetables • Economic benefits of IPM • Environmental and health benefits of IPM

Introduction

Integrated pest management (IPM) seeks to manage pests in an economically efficient and environmentally sound manner. Given the multiplicity of IPM practices on tropical vegetables, and the diversity and levels of impacts, no one method is suitable for all IPM impact assessments. Due, in part, to the cost of rigorous assessment, IPM impact studies have been selective in the programs and practices targeted for evaluation and have varied in their depth. Stated another way, there have been

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relatively few rigorous impact assessments of IPM. This chapter provides a summary of economic and environmental impact assessments of IPM on tropical vegetables. It focuses primarily, but not exclusively, on studies completed on the IPM Collaborative Research Support Program (CRSP) (currently known as Innovation Lab (IL). Methods for measuring IPM impacts are briefly reviewed, followed by results of empirical studies. Finally lessons are drawn for IPM programs and for IPM impact assessment.

Measuring IPM Impacts

Virtually all IPM programs aim to influence economic, health, and environmental outcomes by managing pest pressures and reducing pesticide use. To be viable, IPM packages must raise incomes to farmers, mainly achieved by reducing crop losses and lowering expenditures on purchased pesticides. Economic outcomes may be measured at the individual farm level or at a more aggregate level for producers and consumers in a given market. Health and environmental outcomes may be measured at the individual level or as an average effect over a geographic area. Within economic outcomes, impacts on poverty can be been assessed in addition to impacts on average income.

Major steps in an IPM impact evaluation include: (1) assessing IPM adoption, (2) measuring economic impacts, and (3) assessing health, environmental or other effects. The adoption component can be divided into defining an IPM adoption measure and assessing the rate of adoption over time. The economic evaluation incudes assessing plot/farm-level economic effects and estimating aggregate or market level effects.

Assessing Adoption

IPM includes individual pest management practices as well as strategies that include combinations of practices or tactics. A commodity- and location- specific definition of IPM is needed before the level of spread or adoption can be measured for a specific program. Defining IPM means identifying individual IPM practices and grouping them into IPM adoption levels (such as high, medium, and low) or weighting them on an adoption scale. Levels or scales need defining because producers may selectively adopt IPM practices, and therefore IPM adoption can be a matter of degree. Scientists and others can provide information to help group (Rajotte et al. 1985; Napit et al. 1988), or scale (Hollingsworth et al. 1992) practices so that higher levels represent progress in achieving IPM objectives.

Once the measure of IPM uptake has been defined, IPM spread among the target population can be measured or projected. A baseline survey can be conducted at the start of a program and again at the time of evaluation. This longitudinal comparison facilitates attribution of IPM adoption to an IPM program. Care must be taken to ensure that the sample frame is the correct one – that all potential adopters are included.

Often adoption analysis is needed not only to attribute IPM adoption to a particular program, but also to predict future adoption of IPM practices. Even if some adoption has already occurred, total or even partial adoption may not have occurred yet. While extension agents or other experts could be asked to provide adoption projections, a more rigorous analysis would use survey data and a statistical model to predict adoption based on socio-economic and other characteristics of the households (e.g., Moyo et al. 2007).

Measuring Economic Impacts

Economic impacts of IPM can be assessed at both the user and societal levels. User effects primarily include input cost changes and improved profitability associated with yield effects (production losses saved from pests), but can include changes in income risk. Societal impacts include changes in the economic welfare of producers and consumers or in poverty rates resulting from market-level changes in production and prices.

For farmers, IPM adoption implies changes in production or storage practices, costs, and returns. Budgets are commonly used to assess those changes. Data are required on inputs, outputs, and prices. Budgets for pest management alternatives can be compared using data from replicated on-farm experiments or from user surveys. When using experimental data, budgets may incorporate only those costs that differ across treatments, and results are subjected to analysis of variance to test for significant differences in mean profitability by treatment (Swinton et al. 2002; Norton and Swinton 2010). On-farm experiments often involve some control over management practices, and farmers are often included in trials because conditions on their farm are good. For these reasons, caution is needed when extrapolating results to the general population, but by developing a budget for each level of adoption, changes in net returns can be linked to levels of IPM adoption.

If costs of production are measured through surveys of adopters, care must be taken to randomize villages and households in the surveys and to account for selection bias among adopters in the subsequent statistical analysis (Feder et al. 2004).[1] Selection bias means that unobserved factors associated with adoption may also affect the outcome (e.g. more skilled farmers are most likely to adopt) and these factors may be falsely attributed to positive benefits from IPM adoption. Fortunately, randomized controlled trials, instrumental variables, propensity score matching,

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[1] Measuring the extent of adoption assumes an interest in the market-level effects of the IPM program. If relative profitability of specific IPM practices is the only interest, perhaps to make producer level recommendations, adoption analysis may be skipped.

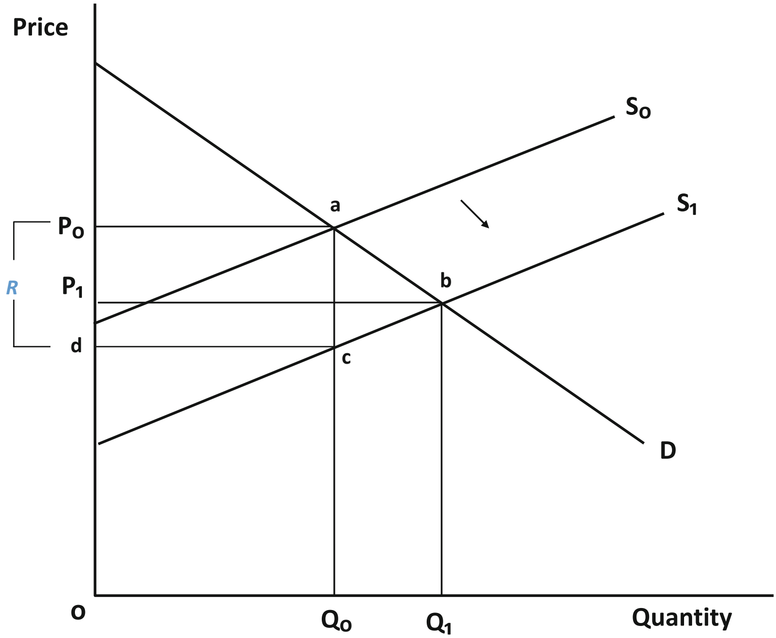

Fig. 14.1 IPM benefits measured as changes in economic surplus (Source: Norton et al. 2005)

and other statistical techniques can be used to minimize problems associated with selection bias (Khandker et al. 2010).

Cost of production budgeting can be used to judge the profitability of practices being developed or recommended, or of practices already adopted. Budget information is also as an input into a market-level assessment of the economic benefits and costs of an IPM program. Market-level impacts are obtained by combining estimated farm-level changes in costs and yields with adoption estimates and with information on responsiveness of supply and demand to price changes. The resulting changes in "economic surplus" can be included in a benefit cost analysis that accounts for distribution of benefits and costs over time and facilitates comparisons with other investments.

Widespread adoption of IPM over large areas affects crop prices, cropping patterns, producer profits, and economic welfare of producers and consumers. These changes are illustrated in Fig. 14.1 (Taken from Norton et al. 2005), where S_0 represents the supply curve before adoption of an IPM package, and D represents the demand curve. The initial price and quantity are P_0 and Q_0. Suppose IPM leads to savings of R in the cost of production, reflected in a shift down in the supply curve to S_1. This shift leads to an increase in production and consumption of Q_1 (by $\Delta Q = Q_1 - Q_0$) and the market price falls to P_1 (by $\Delta P = P_0 - P_1$). Consumers are better off because they can consume more of the commodity at a lower price. They benefit from the lower price by an amount equal to their cost saving on the original quantity ($Q_0 \times \Delta P$) plus their net benefits from the gain in quantity consumed. Their total benefit is represented by the area P_0abP1.

Although they may receive a lower price per unit, producers can be better off too, because their costs have fallen by R per unit, an amount greater than the fall in price. Producers gain the increase in profits on the original quantity ($Q_0 \times (R - \Delta P)$) plus the profits earned on the additional output, for a total producer gain of P_1bcd. Total benefits are obtained as the sum of producer and consumer benefits.

The distribution of benefits between producers and consumers depends on the size of the fall in price (ΔP) relative to the fall in costs (R) and on the nature of the supply shift. For example, if a commodity is traded and production in the area producing the commodity has little effect on price, most of the benefits would accrue to producers. If the supply curve shifts in more of a pivotal fashion as opposed to a parallel fashion as illustrated in Fig. 14.1, the benefits to producers would be reduced. Early adopters of the IPM package are more likely to benefit, while late adopters, and those that do not adopt, may be disadvantaged due to the fall in prices. Formulas for calculating consumer and producer gains for a variety of market situations are found in Alston et al. (1995).

The most difficult aspect of an economic surplus analysis is the calculation or prediction of the proportionate shift in supply following IPM adoption. Cost differences from adoption of the IPM package and adoption rates must be measured carefully. The producer surveys and information on cost and yield changes in field trials or from analysis of survey data can be used to obtain the information required to estimate the supply shifts. Once changes in economic surplus are calculated or projected over time, benefit/cost analysis can be completed in which net present values, internal rates of return, or benefit cost ratios are calculated. The benefits are the change in total economic surplus calculated for each year, and the costs are the public expenditures on the IPM program.

Aggregate or market level economic effects can be distributed in a variety of ways. Regression analysis can help identify who is likely to adopt IPM, differentiated by farm size, household characteristics, etc. It can be used as well to estimate the effects of IPM on household income, pesticide use, health, or other factors, taking into account farm size and household characteristics.

IPM adoption can affect poverty. While the poor may gain as producers, they may also benefit as consumers due to lower food prices, as the poor spend a high proportion of their income on food. Economic surplus analysis can be combined with household-level data analysis to assess changes in poverty resulting from adopting IPM (Moyo et al. 2007).

Measuring Health and Environmental Impacts

IPM practices may have health and environmental benefits that are valued by individuals but are not priced in the market. Changes in use of pesticide active ingredients associated with changes in pest management practices or in the number of pesticide applications have often been used to assess these impacts. However, specific pesticides and how, when, and where they are applied affect health and the environment in different ways, thus suggesting a need for more refined analysis.

Assessing physical and biological effects of pesticide use that occur under different levels of IPM is difficult. Pesticides have many distinct acute and long-term effects on sub-components of health and the environment such as mammals, birds, aquatic life, and beneficial organisms. Because these effects are generally not priced in the market, it is difficult to know how heavily to weight various health and environmental effects compared to each another and to income effects.

Many assessments of health and environmental effects of IPM have used non-location specific risk indicators that use information on pesticides applied and the method of application. An example is the environmental impact quotient (EIQ) developed by Kovach et al. (1992). Indexing methods involve subjective weighting of risks across environmental categories. The indices perform two tasks: (1) identify the risks of pesticides to the individual categories of health and the environment, such as groundwater, birds, beneficial insects, and humans, and (2) aggregate and weight those impacts across categories.

As summarized by Norton and Swinton (2008), the EIQ uses a discrete ranking scale in each of ten categories to identify a single rating for each pesticide active ingredient (a.i.). The categories include acute toxicity to non-target species (birds, fish, and bees), acute dermal toxicity, long term health effects, residue half-life (soil and plant surface), toxicity to beneficial organisms, and groundwater/runoff potential. The EIQ groups the ten categories into three broad areas of pesticide action: farm worker risk, consumer exposure potential, and ecological risk. The EIQ is then calculated as the average impact of a pesticide AI over these three broad areas, and is reported as a single number. The EIQ is defined for specific pesticide active ingredients. In order to assess the actual damage from pesticide use on a specific field, the EIQ can be converted into a “field use rating.” If only one pesticide is applied, this rating is obtained by multiplying the pesticide’s EIQ by its percent a.i. and by the rate at which the pesticide was applied.

To reduce the subjectivity on the weights, a method such as contingent valuation or choice experiments can be used to derive willingness to pay to reduce pesticide risks. Contingent valuation uses a survey to collect data on people’s stated willingness to pay (WTP) to reduce the risk of pesticides to various categories of health and environment (Cuyno et al. 2001). The WTP data can be linked to pesticide use data to arrive at a value for a change in pesticide use.

Results of IPM Impact Studies for Tropical Vegetables

IPM impact assessments have been undertaken in several countries in Asia, Africa, and Latin America. Most have involved economic evaluations but some have included health and environmental or other impact assessments.

Economic, Health, and Environmental Impacts

IPM economic impact studies on tropical vegetables in Asia have primarily focused on countries targeted by the IPM CRSP (IL): The Philippines, Indonesia, Bangladesh, India, and Nepal.

The Philippines

The Philippines vegetable IPM program, which began in 1994, focused on eggplant and onion. Baseline surveys found that Philippine farmers apply insecticides to eggplant twice a week to control fruit and shoot borer (FSB) (*Leucinodes orbinales*) (Miller et al. 2005). Targeting this crop for an IPM program, the IPM CRSP tested a series of alternative practices, including varying the number of sprays combined with removing damaged fruits and tips at varying intervals. Partial budgets were constructed for each combination to arrive at the recommended practice (Norton et al. 2005). Results of the analysis found that for eggplant, weekly hand picking of damaged fruits and shoots combined with spraying Brodan every 2 weeks as opposed to the existing practice of spraying every 3 days net an additional $2500 per hectare per season (Miller et al. 2005). Bacterial wilt (*Ralstonia solanacearum*) is another problem on eggplant and a grafting technique was implemented based on one developed in Bangladesh. Budgeting and economic surplus analyses were completed and an assessment of nutritional impacts resulting from the additional eggplant consumption in the diet (Mutuc 2003). The per-unit cost of eggplant production dropped 14 % in Nueva Ecija province for grafted plants and dropped 5 % in Pangasinan province. Bacterial wilt affected more than 5 % of the eggplant area in the provinces (and up to 50 % in some areas). Assuming adoption of grafted eggplant varieties on up to 70 % of the 5 % affected area, calorie consumption increased by roughly half a kilocalorie per person due to consumption adjustments following adoption of grafted eggplant.

The onion IPM program in the Philippines focused on practices to reduce problems with nematode (*Meloidogyne graminicola*), cutworm (*Spodoptera litura*), weeds such as purple nutsedge (*Cyperus rotundus*), and the disease pink root (*Phoma terrestris*). Partial budgets were constructed to assess the most profitable practices to recommend, and farmers were targeted with training programs, including farmer field schools (FFS). The adoption and the economic and pesticide impacts of IPM practices on onions were evaluated at the time of the research (Francisco and Norton 2002; Cuyno et al. 2001), as well as several years after the program ended using data from a farm-household survey (Sanglestsawai et al. 2015). An analysis of environmental and health benefits of onion IPM was completed for six villages (Cuyno et al. 2001). Initial economic analyses of benefits of weed and cutworm control found that the combination of applying NPV and rice hull burning gave the highest returns and were projected to have an aggregate economic benefit over 15 years of more than $20 million in the San Jose onion growing region and $3.5 million in the Bongabon region, both in Nueva Ecija Province (Francisco and Norton 2002). The value of environmental and health benefits due to reduced use of pesticides was $150,000 in the six villages surveyed (Cuyno et al. 2001). Sanglestsawai et al. (2015) conclude that the onion IPM program in the Philippines as promoted through FFS significantly reduced pesticide use but had little effect on farm profits.

A targeted evaluation of the impacts of a specific FFS intervention on insecticide use was conducted by Yorobe et al. (2011). The study was careful to control for selection bias, unlike many other FFS evaluations (such as Olanya et al. 2010). It surveyed a random sample of onion growers, some of whom received IPM training in 2008. Using an instrumental variable approach to control for endogeneity and selection bias, the study found that FFS-trained farmers had lower insecticide expenditures than non-trained farmers.

Bangladesh

The IPM CRSP program began in 1998 in Bangladesh with a focus on eggplant, cabbage, gourds, okra, and tomatoes in rice based systems. Implemented through Bangladesh Agricultural Research Council (BARC) and housed in the Horticultural Research Center of the Bangladesh Agricultural Research Institute (BARI), several promising technologies were developed. Among these technologies are soil amendments to control soil borne diseases in eggplant, grafting to control bacterial wilt in eggplant, improved weeding strategies for cabbage, and germplasm screened for eggplant fruit and shoot borer. Several economic impact studies have been completed for this IPM program. An early analysis of returns to the soil amendment (eggplant) and weed management (cabbage) research was conducted as part of an MS thesis (Debass 2000). Economic surplus models were solved and net present values of $14–29 million were projected over 30 years for the soil amendments and $15–26 million for the weed IPM practices with most of the benefits were spread over two regions of the country.

Rakshit et al. (2011) combined yield and cost data from on-farm trials with projected adoption rates from a survey of 300 farmers and from expert opinion and conducted an economic surplus analysis of the benefits of Cuelure pheromone traps to mass trap the fruit fly (*Bactrocera cucurbitae*) on sweet gourd. A yield change of up to 50 % was assumed and benefits were projected over 15 years. Sensitivity analysis was conducted for key parameters resulting in an estimated range of benefits from $2.7 million to $6.3 million. The technology has proven to be popular with farmers and therefore an ex post farmer survey was completed to refine the benefit estimates (Ahsanuzzaman 2015). Instrumental variables and propensity score matching were each used to estimate yield and cost effects while controlling for selection bias. Data were obtained from a survey of 317 farm-households in four districts in Bangladesh: Jessore and Magura in the south-west, Comilla in the east, and Bogra in the north. Almost half the farmers adopted the mass trapping practice, average yields were 34 % higher and costs were not significantly different for adopters and non-adopters. While the yield effect is slightly lower than that estimated by Rakshit et al. (2011), adoption has been substantial leading to even larger total economic benefits than those estimated in the first study.

Ricker-Gilbert et al. (2008) estimated the cost-effectiveness of alternative methods for diffusing IPM practices in Bangladesh. While the primary purpose of the study was not to assess economic impacts of IPM, it did assess adoption rates of various IPM practices that result from several diffusion approaches, assessed per farmer benefits from adopting various IPM practices on vegetables, and compared the amount of economic benefits received per farmer to the costs of training the farmer with various diffusion approaches and for the various types (complexities) of IPM practices. For most practices, field days provided the most benefits per dollar spent (around $30 per dollar spent on training). Harris et al. (2013) conducted a follow-up to that study and derived the optimal mix of diffusion approaches to achieve maximum economic benefits. She too came to the conclusion that field days are highly cost effective.

India

India has had a long history of both the public and private sectors developing IPM solutions to pest management problems. For example, Bio-control Research Laboratories (BCRL) in Bangalore, coordinating with the Indian Council for Agricultural Research, Tamil Nadu Agricultural University, and other institutions has produced biocontrol products and conducted training for three decades. The IPM CRSP worked with Tamil Nadu Agricultural University, The Energy Resources Institute, and others to implement IPM programs on vegetables in Southern India and other areas in the country. The onion IPM program was evaluated using a survey of 264 onion farmers randomly selected in Perambalur and Trichy districts in Tamil Nadu (Natarajan 2013). Data were analyzed with propensity score matching to assess the impacts of IPM on yield, income, and pesticide use. The results indicated that IPM adopters had a significantly higher yield than do the non-adopters. IPM farmers obtained 2500 kg higher yield per hectare than did the non-IPM farmers and $750 higher income per hectare. The difference in incomes is partly attributable to a $124 per hectare reduction in pesticide expenditures by onion IPM growers.

In 2006, farmers in Tamil Nadu began to report that a new pest was affecting papaya (*Carica papaya L.*) (Regupathy and Ayyasamy 2010). In July 2008, Dr. R. Muniappan of the IPM IL collected specimens of the pest, which was yet not a severe problem but was infesting a papaya tree in an orchard at Tamil Nadu Agricultural University in southern India (Muniappan et al. 2009). The pest was identified by Dr. Muniappan as the papaya mealybug *Paracoccus marginatus* (Hemiptera: Pseudococcidae), and a classical biological control program was initiated. Three parasitoids, *Acerophagus papayae*, *Pseudleptomastix mexicana*, and *Anagyrus loecki* (*Hymenoptera*: *Encyrtidae*), were imported from Puerto Rico in July 2010, and *A. papayae* was multiplied and released. In the 2 years between the identification of *P. marginatus* and the arrival of the beneficial parasitoids, papaya losses became severe despite heavy pesticide use, and the pest spread to other crops as well. Within 5 months of first releasing the beneficial insects, excellent control of the papaya mealybug was obtained, pesticide usage was reduced, and production and income were increased. Economic benefits of this classical biological control program were estimated using data on crop losses due to the pest and economic surplus analysis. The annual economic benefits for the five most important crops affected by the biocontrol program ranged from $121 million to $309 million, and the net present value of benefits over 5 years totaled $524 million to $1.34 billion.

A reduction in pesticide use on vegetables was evaluated for a non-IPM CRSP farmer field school program on IPM for Jammu and Kashmir, India (Sharma et al. 2015). A field environmental impact quotient (FEIQ) that considered the toxicity of the pesticides was used for the evaluation. A sample of 80 IPM-trained and 60 non-IPM farmers were selected for the evaluation. Pesticide use by weight in the non-IPM villages was greater in the cases of cauliflower and eggplant by 19 % and 39 %, respectively, but it was less by 12 and 26 % for cabbage and okra. Overall, the IPM-trained farmers reduced pesticide use (active ingredients), by weight by 10 %, and by treatment frequency by 29 %. However, the FEIQ of pesticide use was higher in the IPM villages compared to the non-IPM villages, implying the IPM farmers applied more toxic pesticides. Unfortunately the study gives no details on the content of the IPM program nor who administered the FFS, reducing the usefulness of the evaluation.

IPM economic impact studies on tropical vegetables in Latin America have primarily focused on IPM CRSP (IL) targeted countries: Ecuador, Honduras, and Guatemala.

Ecuador

IPM vegetable program evaluations in Ecuador have focused on potatoes, plantain, and Andean fruits. While not strictly vegetables, the first two crops play an important role in vitamin and mineral nutrition, much like vegetables. The potato IPM CRSP program in Ecuador began in 1997 and was undertaken by the national agricultural research institute (INIAP) with the assistance of the International Potato Center and the IPM CRSP, Virginia Tech and Ohio State. It focused on three primary pests, Late Blight (*Phytoptera infestans*), Andean potato weevils (*Premnotrypes vorax*), and Central American tuber moth (*Tecia solanivora*). An assessment was made of the economic impacts of the partially late blight resistant Fripapa 99 potato variety, a set of IPM practices to manage Andean weevil, and a set of IPM practices to manage tuber moth (Quishpe 2001). Three producing regions were included in the analysis, and consumption was assumed to occur anywhere in the country and through trade in other countries. Economic surplus and benefit cost analyses were conducted (Quishpe 2001; Barrera et al. 2002). Fripapa 99 produced an internal rate of return of 27 % and generated an additional $600 per hectare compared to the previous variety and roughly $50 million in net benefits. The IPM program for

Andean Weevil was estimated to save $87 per hectare in the Central region and $42 per hectare in the South. The IPM program against the tuber moth in the North was projected to generate net benefits of $62 per hectare.

The Ecuador potato IPM research and technology diffusion program supported by the IPM CRSP ended in the north in 2003. Three years later and again 9 years later, ex post economic impact evaluations were conducted to assess the extent of spread and the durability of the results (Mauceri et al. 2007; Carrion 2013). The first impact assessment results showed that IPM increased profits per hectare by $270–$560 per hectare in the Carchi (northern Ecuador) region. IPM adoption was 10–32 % depending on the practice. The second set of ex post results showed that IPM adoption continues in the area but with a lower proportion of farmers fully adopting all practices and a higher proportion adopting low to moderate number of practices as compared to the earlier period (Carrion 2013). Almost all potato farmers in the area use some IPM practices, reflecting a major increase in IPM use. Farmer-to-farmer spread has supplanted formal training and outreach mechanisms. Results also show that IPM adoption significantly lowers pesticide use and saves production costs for adopting farmers. After controlling for the endogeneity of IPM adoption, it was found that adoption significantly decreases pesticide expenditures (Carrion 2013).

Baez (2004) applied economic surplus analysis to estimate the benefits of Plantain IPM in coastal Ecuador. Benefits ranged from $50 million to $53 million over 15 years.

Honduras

Sparger et al. (2011) evaluated the economic benefits of IPM on eggplant, onion, pepper, and tomato in Honduras. They also examined the distribution of the benefits to producers and consumers and to people at various income quintiles. Discounted net benefits totaled more than $17 million over 15 years (Tables 14.1 and 14.2), with the largest producer benefits realized for peppers and the largest consumer benefits realized for tomatoes. Eggplant had the largest poverty- reducing impact with tomatoes the second largest.

Table 14.1 Net present value of IPM technologies by crop in Honduras (millions of USD)

	Eggplant	Pepper	Onion	Tomato	Total
Grafting	2.99				2.99
Biological controllers	0.17	2.65	0.02	4.01	6.85
Solarization		2.12	0.51	3.18	5.81
Pressure regulating valve			1.44		1.44
Cowpea green manure				0.47	0.47
Total	3.16	4.77	1.97	7.66	17.56

Net present value is calculated using a 5 % discount rate over a 15 year period

Table 14.2 Summary of IPM impact assessment results for tropical vegetables

Country, author(s), date	Crop	IPM practice(s)	Net economic benefits (millions)	Other benefits (poverty, nutrition, environment)
Philippines, Mutoc (2003)	Eggplant	Grafting		Increase of 0.09–0.6 kcal/person/day in Nueva Ecija
Philippines, Francisco and Norton (2002)	Onions	NPV and cultural	$23.5	
Philippines, Miller et al. (2005)	Eggplant	Cultural		$2500/ha to producers
Philippines, Cuyno et al. (2001)	Onions	Cultural		$150,000 in environmental benefits to six villages
Philippines, Sanglestsawai et al. (2015)	Onions	FFS IPM diffusion		Significant reduction in pesticide use
Bangladesh, Debass (2000)	Eggplant, cabbage	Cultural practices	$26–$29	
Bangladesh, Rakshit et al. (2011)	Sweet Gourd	Pheromone traps	$3–$6	
India, Natarajan (2013)	Onions	Cultural		$750/ha to producers; $124/ha in pesticide cost savings
India, Myrick et al. (2014)	Papaya, tomato, eggplant, others	Biocontrol	$524–$1340	
Ecuador, Barrera et al. (2002)	Potatoes	Resistant variety	$108	$209/ha in pesticide cost savings
Ecuador, Mauceri et al. (2007)	Potatoes	Multiple		$270–$560/ha to producers
Ecuador, Carrion (2013)	Potatoes	Multiple		
Ecuador, Baez (2004)	Plantain	Sanitary leaf pruning, weevil traps	$50–53	$8–9.5 million benefits accrue to labor
Honduras, Sparger et al. (2011)	Eggplant, tomatoes, peppers, others	Grafting, solarization, cover crop, etc.	$17	$5 to the poor
Honduras, Secor (2012)	Multiple	Multiple	$70	Several improvements in gender indicators
Uganda, Debass (2000)	Beans	Seed dressing	$202	
Mali, Nouhoheflin et al. (2009)	Tomato	Host free period	$21–$24	

Secor (2012) assessed how benefits from IPM research accrue to women by examining the crops and technologies and the proportion of income that accrues to women. Crops and specific technologies that could benefit women are difficult to identify, but he developed and tested a framework to do so. The application to an IPM program in Honduras showed that crop size is one of the most important factors affecting the flow of research-induced benefits to women. However, a key parameter in the gender distribution benefits is the propensity of women to adopt specific technologies.

Turning to Africa, impact studies were conducted on the IPM CRSP in collaboration with other institutions and projects to assess poverty impacts of virus resistant groundnuts (Moyo et al. 2007) and consumers' willingness to pay for vegetables that are free from pesticide residues (Bonabona-Wabbi et al. 2014).

Uganda

Peanut production is constrained by the prevalence of viruses and diseases, the most common being Groundnut Rosette disease. Groundnut Rosette disease causes major losses in peanut production in Africa. The International Crop Research Institute for Semi-Arid Tropics (ICRISAT), and the USAID-funded Peanut CRSP, in collaboration with national agricultural research systems developed and released varieties with resistance to Rosette virus in Malawi and Uganda, countries with high incidence of poverty. Moyo et al. (2007) estimated the overall economic impacts of the research that developed Rosette Virus-resistance peanut in Uganda, focusing on the regions in the two countries where peanuts are most prevalent, and quantifying the effects of research on the livelihoods of the poor. They calculated changes in economic surplus that result from adoption of the varieties and then assessed the effects on the poverty rate. Household production, consumption and expenditure data were used to compute poverty indices which permitted poverty decomposition by income group. Realized research benefits from the economic surplus model were incorporated into the poverty indices to estimate how households of differing economic profiles moved relative to the poverty line as their incomes were affected by the improved technology. The net present value of economic benefits for the period from 2001 to 2015 was projected at $47 million at a 5 % discount rate. Changes in poverty rates were calculated under alternative assumptions about adoption by farmers in various income strata. A Probit model was used with the farm-household data to predict adoption by income strata. A reduction in the poverty rates of 0.5–1.5 % was calculated for the region.

Bonabona-Wabbi et al. (2014) conducted an experiment with about 200 rural and urban participants to assess consumer and producer willingness to pay for groundnuts that are free from pesticide residues. Participants were given actual currency and allowed to keep the money or to spend it on pesticide free groundnuts. In both cases, participants agreed to consume the nuts. Consumers were willing to pay about $14 (343 Uganda shillings) to avoid pesticides on their groundnuts and producers about $11.

Debass (2000) used partial budgeting and economic surplus analysis to assess the economic benefits in Uganda of using seed dressing on beans to control rodent infestation and fungal infection. He estimated an economic benefit of $202 million over 20 years.

Mali

Nouhoheflin et al. (2009) assessed the economic benefits of IPM technologies aimed at reducing the virus problem in tomatoes in Mali. Surveys were conducted with producers, scientists, and other experts, and both farm-level and societal-level benefits were projected over time. Adoption of the practice of a host-free period reduced insecticide cost by more than $200/ha. The profit from adopting virus-tolerant seeds ranged from $1200 to $4800/ha. Economic surplus analysis was conducted and the benefits for Mali over 18 years were estimated to reach as high as $21.6 million under a closed economy assumption and $24 million under an open economy assumption.

Conclusion

IPM impact assessment is crucial for making meaningful recommendations to farmers, for demonstrating the value of IPM programs, and for assessing who will adopt so that programs can be tailored to audiences to obtain consistency with program goals. These assessments can focus on various objectives but most have evaluated per hectare or market-level income effects. The total estimated impacts of IPM on tropical vegetables exceed $500 million for just the small set of careful empirical evaluations that have been completed, making tropical vegetable IPM research and extension a highly-profitable public investment.

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