Chapter 1

IPM for Food and Environmental Security in the Tropics

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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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