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INVERTEBRATES IN RICE PRODUCTION SYSTEMS: STATUS AND TRENDS

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TABLE OF CONTENTS

	Page
List of Tables	iv
List of Figures	iv
Acknowledgement	v
Executive summary	7
Invertebrates in rice-based production systems: historical perspective	7
Current understanding of invertebrates in rice systems	8
Regional analysis of relevant invertebrate species in rice ecosystems	9
Areas under risk of critical loss of invertebrate diversity	10
Current constraints and opportunities	11
- Constraints	11
- Opportunities	11
Preparing for the future	11
Priority action	13
- Strengthening pesticide registration and marketing regulation	13
- Accreditation of plant protection service providers	13
Funding biodiversity research	13
Recommendations	13
- Policy interventions	13
- Research and development	14
- International support	14
I. Introduction	15
II. Invertebrates in rice-based production systems from an historical perspective	16
II.1. Rice and rice production systems	16
II.2. Diversity of invertebrates in rice production systems	18
II.3. History of rice ecosystems before the green revolution	19
II.4. Important milestones that have impacted on rice ecosystems	20
II.4.1. Rice intensification	21
II.4.2. Overuse of nitrogen fertilizer	21
II.4.3. Abused use of pesticides	23
II.4.4. Effects of pesticides on invertebrates	25
II.4.5. Loss of rice varietal diversity	26
II.4.6. Impact on invertebrate diversity	27
II.5. Shift in attention after large outbreaks of BPH	29
II.5.1. Outbreaks during rice green revolution	29
II.6. Successful case histories	30
II.6.1. BPH resistance breeding	30
II.6.2. International conference in 1977	30
II.6.3. The Indonesian story	30
II.6.4. FAO-IPM inter-country program	31
II.6.5. Farmer participatory research	31
II.6.6. International conference of 2008	32

III. Current understanding of invertebrates in the rice systems 35
III.1. Effects of RGR technologies on invertebrate pest diversity 35
III.2. Ecology of the invertebrate food web in rice production systems 36
III.3. Status and trend in biological control agents in rice ecosystems 40
III.3.1. Classical biological control of rice pests 40
III.3.2. Conservation biological control of rice pests 41
III.3.3. Ecological engineering 42
III.4. Impact of different practices on invertebrates 44
III.4.1. Impact of fallowing 44
III.4.2. Impact of crop intensification 44
III.4.3. Impact of land changes 45
III.4.4. Impact of synchronous and asynchronous planting 45
III.4.5. Impact of tillage 46
III.4.6. Impact of aerobic and anaerobic seeding 47
III.4.7. Impact of irrigation 47
III.4.8. Impact of fertilizer application 47
III.4.9. Impact of pesticide application 48
III.5. Ecosystem functions 50
III.6. Contributions to livelihoods 53

IV. Regional analysis of the most relevant invertebrate species in rice ecosystem 53
IV.1. Soil ecosystem engineers 57
IV.2. Biological control agents 57
IV.3. Herbivores 57

V. Areas under risk of critical loss of invertebrate diversity and related ecosystem services 59

VI. Current constraints and opportunities 63
VI.1. Constraints 63
VI.1.1. Insecticide abused use 63
VI.1.2. Herbicide misuse 63
VI.1.3. Nitrogen fertilizer overuse 63
VI.1.4. Hybrid rice and overuse of chemical inputs 63
VI.2. Opportunities 64
VI.2.1. Attention to food safety 64
VI.2.2. Reduction of insecticide use 64
VI.2.3. Judicious use of herbicides 64
VI.2.4. Ecological engineering 64
VI.2.5. Real-time nitrogen management 65
VI.2.6. Rice-fish culture 65

VII. Looking forward: Preparing for the future 65
VII.1. Producing more rice with less water 65
VII.2. Pesticide hazards and resistance 66
VII.3. Cropping systems and cultural practices to improve biological control 67
VII.4. Varietal diversity to enhance invertebrates 69
VII.5. Making pest and biological control agents monitoring available to small-scale farmers 69
VII.6. Regional analysis of irrigated rice ecosystems 70

VII.7. Analysis of the irrigated rice vs. aerobic rice in relation to stability 70
VII.8. Main gaps in the scientific knowledge 70
VII. 8.1. Quantifying biodiversity and ecosystem services 70
VII.8.2. Valuation of ecosystem services in monetary values 71
VII.8.3. International collaboration 71
VII.8.4. Projected effects of climate change 71
VII.9. Priority action 72
VII.9.1. Strengthening and harmonizing pesticide registrations and marketing 72
VII.9.2. Accreditation of plant protection service providers 73
VII.9.3. Funding biodiversity research 74

VIII. Conclusions 74
VIII.1. Policy interventions 75
VIII.2. Research and development 75
VIII.3. International support 76

Literature Cited 77

List of Tables

No.	Title	Page
1	World rice area and production by region in 2010	17
2	World rice area by environment in 2010	18
3	Diversity of invertebrates in traditional rice production systems in Asia	19
4	Nitrogen fertilizer use in selected countries in 2001 and 2007	24
5	Invertebrate/arthropod diversity in irrigated lowland modern variety rice production systems in Asia	28
6	Herbivore and natural enemy diversity in traditional and modern variety rice production systems in Asia	29
7	Comparison of invertebrate diversity and abundance between the rice canopy and paddywater in a Philippine farmer's irrigated rice field	29
8	Planthopper outbreaks in Asia's rice production areas in 2009	33
9	Shift of rice insect pest status due to green revolution in Bangladesh	36
10	Parasitoids and predators attacking yellow stem borer in deepwater rice in Bangladesh	41
11	Effect of tillage on invertebrates in rice fallow fields and bunds	47
12	Some general effects of insecticides on soil-inhabiting and aquatic invertebrates	49
13	Effects of the adoption of IPM strategies on arthropod diversity and abundance at IRRI research farm in Los Baños, Philippines	52
14	Regional analysis of the status and trends in invertebrates of rice production systems	54
15	Diversity of invertebrates feeding on rice plants, by region	58
16	Frequency of insecticide application to rice in selected Asian countries in 1992 and 2011	61
17	Indicators of invertebrate biodiversity and pest regulatory service loss leading to riceplanthopper outbreak potential in selected Asian countries	62
18	Examples of single field cultural control methods, cultural control methods requiring community action, and cultural practices that disturb natural enemies	68

List of Figures

No.	Title	Page
1	The second wave of planthopper outbreaks in some Asian countries	34
2	Mechanism of invertebrate food web functioning in tropical irrigated rice	39
3	Invertebrate food web in rice ecosystem	39
4	Ecosystem services of lowland rice	43
5	Components, functions and enhancement strategies for biodiversity in Agroecosystems	51
6	Distribution of irrigated rice areas in the world	59
7	Development of resistance to imidacloprid and fipronil insecticides by BPHpopulations in China	67

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Executive Summary

The Rice Green Revolution (RGR) is a resounding success in expanding food production, and improving the food security and livelihood of hundreds of millions of people. In many countries, however, intensive crop production has depleted the agricultural resource base, jeopardizing future productivity. Agricultural sustainability depends on biodiversity, which is the foundation of ecosystem services contributing to food provisioning, support and regulatory services through ecosystem functions. The new paradigm of agriculture needs to be sustainable crop production intensification which the Food and Agriculture Organization of the United Nations (FAO) calls: 'save and grow'. In this respect, it is very important to better understand the status and trends of invertebrate diversity in rice production systems; review the current and potential contribution of invertebrates to these systems including the pest regulatory functions they provide; and identify possible priorities as to their conservation and utilization. In this context, the FAO Commission on Genetic Resources for Food and Agriculture requested the International Rice Research Institute (IRRI) to undertake a study to review the status and trends of invertebrates in rice production systems.

Invertebrates in rice-based production systems: historical perspective

Invertebrates comprise about 97% of all animal species. In rice ecosystems, the invertebrate group is dominated by the arthropods, particularly the insects. Invertebrates are involved in many diverse functions: herbivory, predation and parasitism, disease vectoring, pollination, production of silk, honey, lac and other products, and decomposition of plant and animal matter. Quantitative assessments of the diversity of invertebrates in rice systems are limited with very few in traditional systems. For example, in traditional rice systems; 450 species were recorded in Japan, 369 in Bangladesh and 748 in Laos; and in irrigated high yielding varieties (HYVs); 765 species were listed in Indonesia, 355 in Bangladesh, 494 in Sri Lanka, 388 in South Korea and 212 in the Philippines.

In the past; rice production systems were based on low levels of external inputs, and mainly dependent on traditional low-yielding varieties or land races, and natural ecosystem functions and services. Around the middle of the 20th century; large irrigation systems were developed, and inorganic fertilizers and pesticides were introduced. The use of inorganic inputs remained low until the advent of the RGR in Asia in the late 1960s. The RGR had an enormous impact on Asian rice ecosystems through the cultivation of HYVs with its associated package of inputs and cultural practices. The package usually came with the HYV seeds, inorganic fertilizers and insecticides. In many countries, farmers were obliged to use all of these inputs including calendar-based insecticide applications. Insecticide inputs were based on the unproven assumption that tropical rice yields are limited by insect pests and that insecticides control these pests. Cropping intensity significantly increased and many traditional varieties were replaced by a few HYVs requiring high external inputs.

The RGR led to misuse of insecticides, and insecticide use went out of control in the high- yielding production systems. This consequently led to increased pest problems and occurrence of secondary pest outbreaks. Overuse of nitrogen fertilizer also contributed to the pest attacks. The major pest to emerge was the brown planthopper (BPH), *Nilaparvata lugens* (Stal). The first response to widespread outbreaks of BPH (and some diseases) was the development of resistant varieties. But BPH adapted to the

first resistant variety (IR26) within 2 to 3 years, and other BPH- resistant cultivars remained viable for only a relatively short time. However; some widely-planted cultivars particularly IR36 and IR64, have shown greater durability.

In the face of this pest challenge, plant protection specialists turned to integrated pest management (IPM). The FAO-led Inter-Country Rice IPM Program trained more than two million rice farmers in 13 Asian countries. IRRI's Farmer Participatory Research program (FPR) began to convince farmers in seven countries of Southeast Asia that in most cases, it is not necessary to apply insecticides in rice production. The trained farmers reduced their insecticide applications by more than half. However, non-trained farmers continued to routinely treat their rice even when planting resistant varieties. After 30 years of farmers' insecticide application on rice, there is still no good evidence that it has increased their yields. Economists could detect no productivity gains from insecticide applications particularly when health and environmental costs are considered.

Due to its effectiveness against BPH and longer residual period; the newly developed insecticide, imidacloprid was widely used in Vietnam, China, South Korea and Japan in the early 1990s, and it seemed to solve the BPH problem. Moreover, during the same period; it appeared that IPM efforts had probably paid off, and insect pests and their natural enemies were in balance. This complacency was shattered in the late 1990s when a second wave of BPH outbreaks erupted in Southeast Asia. The occurrence of serious outbreaks of BPH and white-backed planthopper, *Sogatella furcifera* (Horvath) (WBPH) in China in 2005 was attributed to various reasons primarily to the planthoppers' development of resistance to imidacloprid. Numerous similar outbreaks in Bangladesh, India, South Korea, Laos, Malaysia, Philippines, Thailand and Vietnam were also reported. Alarmed by the big scale of these pest outbreaks, IRRI convened an international conference in 2008 to consider a common control strategy.

Current understanding of invertebrates in rice systems

The green revolution also caused a significant shift in the insect pest composition and rank. In general, the new rice technologies boosted the plant sap feeders and those requiring high moisture for their growth, development and survival, but retarded those pests requiring drier conditions and seeking dry soil for pupation. Rice intensification and greater year-round rice cropping have encouraged monophagous pests.

Although insecticide applications seek to decrease pest populations, they also reshape the food web structure. Insecticides also kill indigenous natural enemies with the greatest effect on surface dwelling predators and parasitoids. This can result in pest outbreaks and increased likelihood of crop damage. Insecticide sprays at the community level usually disturb predator-prey relationships and the food web structure, thus favoring the occurrence of r-strategist pests such as planthoppers. In the IRRI farm, only 142 arthropod species were observed when pesticide use was intensive but the number significantly increased by 2005 after the adoption of IPM in early 1990s. Species diversity is high in Indonesia (765 species) and in Bangladesh (355 species) where pesticide use is low or negligible.

It was previously thought that all natural enemy groups follow insect pests as they move into fields with young, tillering rice plants. However, recent reports have shown that in irrigated tropical rice, the arthropod predators move to the rice fields at a very early stage before the pests, and feed on the abundant detritivores and plankton-feeding insects. On the other hand, the parasitoids probably follow the pest populations.

Due to their diverse life cycles, many arthropod species occupy different habitats within the paddy ecosystem. Natural enemies are not confined to rice fields; many aquatic species live part of their life cycle outside the rice field. The non-rice habitats in the rice ecosystem provide shelter and supplementary or alternate food for natural enemies.

Applications of broad spectrum insecticides disrupt the biocontrol linkages causing economic losses, health hazards and ecological costs to the farmer and the environment. In traditional rice cropping systems, the natural biological system is stable and persists for thousands of years. This ‘conservation biological control’ is the most cost-effective and very valuable to the rice farmer. The RGR technologies disrupted the natural balance by applying insecticides, using excessive nitrogen fertilizers, extending rice monoculture, and clean cultivation. The series of pest outbreaks experienced over four decades, and the experiments on chemical control and varietal resistance have convinced researchers that the traditional system of conserving natural enemies is the best way to maintain the balance and avoid pest outbreaks. Beneficial effects and ecosystem services providing by the beneficial inverteberates in rice production systems is shown in box 1.

Ecological engineering has recently emerged as a pest management approach. It uses cultural practices and ecological knowledge to enhance conservation biological control with a landscape approach. Pioneering work on ecological engineering is currently being carried out in China, Vietnam and Thailand in collaboration with IRRI.

Box 1. Synaptic table showing major groups of beneficial invertebrates in rice production systems

Major group of beneficial invertebrates	Beneficial effect	Good agricultural practices that conserve them	Ecosystem services that are delivered
Parasitoids Ex. Hymenopteran and dipteran flies	Pest control	Abstain from pesticide use Grow nectar forming flowering plants on non-rice habitats	Regulating
Predators Ex. Spiders, dragonfly mired bugs	Pest control	Abstain from pesticide use Allow non-rice vegetation on non-rice habitats Dry and asynchronous tillage	Regulating
Detritivores Ex. Collembolans, Ephydrid flies	Organic matter decomposition and nutrient cycling	Abstain from pesticide use Dry and asynchronous tillage	Supporting
Soil ecosystem engineers Ex. Earthworms, termites, millipedes	Influence soil properties	Abstain from pesticide use Dry and asynchronous tillage Crop rotation Less flooding	Supporting

Regional analysis of relevant invertebrate species in rice ecosystems

Data to carry out a regional analysis of the status of invertebrates in rice production systems are insufficient. Only one study in irrigated rice in Indonesia gives information about the invertebrate food web functions and services which may be applicable to Asian rain-fed lowland rice where water stays in the field for extended periods.

Ecosystem engineers which include plants, animals and microorganisms, play a major role in creating, modifying, maintaining and decomposing organic matter in the various habitats found in rice ecosystems. Invertebrates such as nematodes (eelworms), annelids (earthworms), arthropods (ants, termites) and mollusks are important ecosystem engineers in the soil. Very little is known about the diversity and abundance of invertebrate soil ecosystem engineers inhabiting the different rice cultural types, and a quantitative assessment of their role is lacking.

A large and diverse complex of invertebrate herbivores is active in rice production systems. Of the 527 species of invertebrates so far recorded in rice plants, 97% are insects and 3% are mainly crabs, snails, nematodes and mites. Invertebrate herbivore diversity is highest in Asia (322 species), followed by Latin America and Caribbean (126 species), Africa (110 species), with the least in USA and Europe (37 species).

Many of the invertebrates are natural enemies. Predatory behavior is widespread among insects, spiders and mites while parasitoids are predominantly insects. The diversity and abundance of invertebrates are difficult to separate in the different Asian rice environments thus, a careful literature review would be useful. Information on the invertebrates in other major rice regions is scarce.

Areas under risk of critical loss of invertebrate diversity

Irrigated rice systems are potentially high risk areas of invertebrate and ecosystems services losses because of insecticide misuse and highest rates of nitrogen application in this rice system. Planthoppers are present throughout the Asia-Pacific region, and the Asian rice planthoppers also occur in Africa where about 20% of rice area is irrigated. Latin America, the Caribbean and USA do not have the Asian planthoppers but have other delphacids, e.g. rice delphacid, *Tagosodes orizicoles* which is important though less destructive.

Nitrogen use has tremendously increased in many major rice-growing countries, particularly Thailand, Indonesia, China, Brazil and India from 2001 to 2007. One hundred kilograms of nitrogen per hectare is used as the arbitrary threshold to identify countries at high risk to planthopper outbreaks. Using this threshold; China, Egypt, Malaysia, Iran, Vietnam, Pakistan, Bangladesh, and India qualify as high risk while Indonesia is close behind.

Information on insecticide use in Asian rice is surprisingly poor, and most of the data come from special development programs. However, a significant escalation of insecticide use in rice during the last two decades is very apparent with an average of five applications/season, and some up to eight applications in several countries. Vietnam is the only country where the application has decreased (from 3.9 to 3.2). This is probably a result of the FAO-assisted IPM program, IRRI’s FPR program, the ‘seed, fertilizer and insecticide reduction program’ followed by a mass media campaign, and the government’s recent efforts to curb insecticide misuse. As a result, Vietnam did not experience planthopper outbreaks after 2008.

Based on the insecticide use pattern and the history of planthopper outbreaks, it appears that insecticide applications of three or more times per season reduce invertebrate diversity and pest regulatory services, thus precipitating planthopper outbreaks. Based on the threshold of nitrogen use (100 kg N/ha), the insecticide application of three times per season, and the record of BPH outbreaks in 2009; China, India, Malaysia and South Korea are very high risk areas for BPH outbreaks. Using insecticides at higher rates; Cambodia, Indonesia, Japan, Laos and Thailand are identified as high risk areas. Bangladesh, Iran, Pakistan, the Philippines and Vietnam are at moderate risk because insecticide use is below the cut off rate, but they either experienced BPH outbreaks in 2009 and/or their nitrogen use is high. The 14 rice-growing countries considered in this risk assessment account for 81% of the world's rice area, and 82% of world's rice production.

Current constraints and opportunities

Constraints

The major threat to invertebrate diversity and abundance, and consequent breakdown of rice ecosystem services is the overuse of insecticides. Despite the massive efforts of several special programs to introduce the IPM approach for over more than two decades, insecticide use is still increasing. This is primarily because pesticides are being sold using 'fast moving customer goods' (FMCGs) marketing strategies in most Asian countries. Moreover, regulations to control the use and sale of pesticides like those in the developed world are either lacking or absent in these countries.

Farmers growing hybrid rice use nitrogen fertilizers, insecticides and fungicides at much higher rates than those applied to inbred HYVs. It seems very crucial to critically examine the costs and benefits of hybrid rice culture to farmers, consumers, and the environment.

Opportunities

Irrigated rice ecosystems are blessed with rich and diverse complex of invertebrates that must not be harmed or disturbed by the injudicious application of insecticides, herbicides and nitrogen fertilizer. Reversing insecticide misuse is not easy because of the vested interests of the pesticide industry and the collusion of government officials. Farmers have developed an insecticide use habit which is not based on economic realities. However, curbing insecticide misuse is not an impossible task, but it will need political will and the dedication of government officials.

The early results of ecological engineering, a new approach for maximizing natural biological control, are promising. The leaf color chart (LCC), a simple inexpensive tool which allows farmers to apply nitrogen fertilizer according to crop needs, reduces nitrogen use which in turn lowers the incidence of certain pests and diseases. Rice-fish culture, formerly an important source of free-living fish in the lowlands of Asia which declined during the RGR period, is now regaining popularity as the demand for fish increases. Adoption of rice fish culture also discourages farmers from applying insecticides.

Preparing for the future

The demand for rice is expected to grow in Asia by about one percent per year until 2025. Thus, greater production has to be achieved under increasing pressure on land, water, and labor resources which threatens the sustainability of the rice production base. Water is no longer an abundant natural resource in Asia. In some areas, the pumping of underground water for irrigation is causing arsenic contamination in both irrigation and drinking water. However, research has shown that continuous flooding is not necessary for high rice yields because periodic drainage of rice fields may even bolster yields. Thus in the face of a looming water crisis, such periodic wet and dry irrigated rice is likely to become a more common practice. The impact of such a change on the invertebrate diversity and abundance, and natural biological control, is an important research topic.

The existence of non-rice crops in the rice environment is significant. Crop rotations and crop mosaics increase biodiversity and tend to check the growth of pest populations. In general, mosaics of non-rice crops within large rice blocks encourage the conservation of natural enemies and other invertebrates.

Generally, cultural pest control does not cause environmental pollution and is compatible with other pest management practices. Some cultural practices lead to direct benefits to the farmer when carried out at the individual farm level, while others require community action to be effective. However, some cultural practices like puddling (tillage of flooded fields) and burning of crop residues, seriously disturb the invertebrates and the natural enemy complex.

A resistant variety typically provides effective pest protection for the first few years after release. BPH was managed in Southeast Asia in the 1970s and 1980s largely by the sequential release of resistant varieties. However, such practice is not always available in time to prevent fresh outbreaks. Varietal diversity is usually beneficial and can minimize the risk of pest and disease outbreaks.

Currently, the mechanism and functions of the invertebrate food web and the ecosystem's regulatory services are fairly well understood only in the tropical irrigated rice environment of Asia. This knowledge may be applicable to some extent in Asian subtropical irrigated and rain- fed lowland rice environments. However, investigations have still to be conducted under similar environments in other major rice-growing areas, and other rice environments such as alternate wet and dry systems as well as aerobic rice systems (upland rice).

Reaching the millions of small-scale rice farmers has been always a major challenge for agricultural extension. However, this is being overcome by recent successes in electronic communication; cell phones now offer an opportunity to take pest and biological monitoring results directly to the farmers.

The acute shortage of taxonomists is discouraging research on the biodiversity in rice ecosystems. New investments in education, and the creation of a new taxonomic service are needed. The development of a network which connects biodiversity researchers with a taxonomy hub through remote microscopy is an interesting option.

It is known that ecosystems have valuable built-in pest regulation services, but no monetary value has ever been attached to it. A definite, tangible value should be developed with the participation of economists, social scientists and biologists.

Priority actions

Strengthening pesticide registration and marketing regulations

It is clear that the loss of invertebrate biodiversity and ecosystem services in rice production systems due to insecticides is the root cause of the devastating planthopper outbreaks during the 1970s and again in the 2000s. The case history of IRRI's research farm in the Philippines illustrates that when an intensive and long-standing pesticide schedule is stopped, the ecosystem's pest regulatory service soon revives and pest outbreaks subside. Additional evidence comes from a Philippine farmer's experience of successful rice production without insecticide use for more than 60 successive cropping seasons.

The FAO-led Inter-Country Rice IPM Program in 1980s and IRRI's FPR program in 1990s repeatedly demonstrated that insecticide is the main cause of insect pest problems in rice. However, majority of the trained farmers who initially reduced their insecticide use, later succumbed to aggressive pesticide advertising and marketing. Therefore, farmer's training and experience alone are not enough to quell insecticide misuse. In addition, supplementation of appropriate regulations for pesticide registration and marketing, and their proper implementation are still necessary. Vietnam is presently taking the lead in the governance of pesticide marketing. The governments of the Asian countries need to govern pesticide marketing for the benefit of their own people. International organizations such as FAO are encouraged to promote, foster, and continue engagement dialogue between countries to address such issues.

Accreditation of plant protection service providers

Although many have no technical expertise, pesticide dealers/retailers in Asia play a major role in farmers' pesticide decision making. It is important that only technical personnel should be given the responsibility to recommend appropriate pest management practices including pesticide use. Without their prescription, retailers should not be allowed to disburse pesticide to anyone, and pesticides should be applied only by trained and licensed professionals. Under a Trust Fund project, FAO is currently working with the national governments of Cambodia and Lao PDR to set up and pilot test the development of a functional pesticide dealer licensing and inspection system.

Funding biodiversity research

Research and Development (R & D) activities in developing countries often depend on external funding since their own funds are usually limited. International agencies and environmentalist groups/organizations in the developed world should support and contribute in providing funds for biodiversity research.

Recommendations

The main issues and conclusions were already discussed earlier in this executive summary and will not be repeated here. The main recommendations fall under three headings.

Policy interventions

The following policy interventions are suggested:

1. Revise relevant regulations, rules and laws to control pesticide marketing campaigns (to probably resemble those of the pharmaceutical industry).
2. Inspire and educate the general public and future generations by introducing IPM and ecological engineering at the high school and higher education levels.
3. Empower the grassroot level agriculture department personnel by training and introducing them to IPM and ecological engineering.
4. Mobilize and educate farmers and the general public about understanding ecosystems and services vital for IPM, and ecological engineering through adult-education including Farmers Field Schools, and the electronic mass media including television (TV) and radio.
5. Introduce proficiency tests/licensing for pesticide applicators, and equipment-related legislation (e.g. safety standards, registration)

Research and development

1. Monitor pesticide use and the development of pesticide resistance in farmers' fields.
2. Monitor the pest and natural enemy situation regularly; identify ecosystem health indicators.
3. Establish ecosystem engineering demonstration sites to train agricultural professionals and high school teachers in practical aspects of this approach.
4. Undertake researches on a) diversity and abundance of invertebrates and their food web, and b) their mechanism and functions under different rice environments including alternate wet and dry irrigation systems and upland system.
5. Evaluate effects of rice genetic diversity on invertebrate diversity and pest regulation.

International support

1. Procure funds for invertebrate biodiversity research in rice production systems.
2. Develop manpower particularly in ecology, production, biology and taxonomy.
3. Develop a taxonomic network using remote microscopy system with IRRI as the hub.

I. Introduction

The green revolution led to a quantum leap in food production and bolstered world food security (Mohanthy, 2011). In many countries, however, this intensive crop production has depleted agriculture's natural resource base, jeopardizing future productivity (FAO, 2011). However, there is no option to feed the growing world population except to further intensify crop production. The present paradigm of intensive crop production cannot meet the challenges of this millennium, thus the new 'Save and Grow' paradigm is necessary. It must be sustainable crop production intensification, which will produce more from the same area of land while conserving resources, reducing negative impacts on the environment, and enhancing natural capital and flow of ecosystem services (FAO, 2011).

Pesticides kill pests but they also kill the pests' natural enemies, and their overuse can harm farmers, consumers, and the environment. The first line of defense of the 'Save and Grow' paradigm is a healthy agroecosystem (FAO, 2011) wherein biodiversity (the number and variety of organisms present in a habitat or specific geographic region) is fundamentally important in sustaining soil productivity and pest management. Biodiversity is the foundation of ecosystem services contributing to food provisioning through crop and genetic diversity, support and regulatory services through ecosystem functions (Heong, 2009). In pest management, the two most important ecosystem functions are predation and parasitism which are linked to the diversity of predators and parasitoids.

The soil is the habitat of many diverse species of biota (both flora and fauna). Along with bacteria, fungi, and green algae; invertebrates, namely: nematodes, annelids, arthropods and mollusks are important components of the soil biota which play a very important role in nutrient cycling. In the absence of their activities, organic materials would simply accumulate and litter the soil surface, and there would be no food for plants. Above the ground, a vast complex of predators, parasitoids and parasites which are mostly invertebrates (predominantly insects) is active in crop fields. Without the ecosystem's pest regulatory services, rice production succumbs to frequent pest outbreaks and becomes unsustainable. Although it is difficult to quantify all the benefits of the said services, it can be assumed that rice yields will be substantially reduced in their absence. Currently, almost 90 percent of the rice lands are either irrigated or rain-fed lowlands whose soils are wet during most part of the cropping period. This condition may have profound effect on the soil biota and can exuberate pesticide problems beyond the rice fields.

Natural ecosystems are known to support a high population of soil and above ground invertebrates. However, agricultural ecosystems usually have lower population density of biota (Lal, 1991). This is because agricultural chemicals tend to suppress the species richness and their functions. Insecticides disorient the trophic links of the invertebrate food web leading to the rise of secondary pests such as rice planthoppers (Heong, 2009). Rice green revolution (RGR) technologies that led to the routine application of insecticides and overuse of nitrogen fertilizer are known to create outbreaks of secondary pests such as rice planthoppers in Asia. As a result, Asian rice experienced a wave of rice planthopper outbreaks during the 1970s and again in the late 1990s (http://ricehoppers.net/).

Fortunately, arthropod biodiversity in rice ecosystems has an innate capacity to increase when a suppressing factor such as insecticide is removed (Heong, 2009). Continued outbreaks of rice planthoppers since the late 1990s indicate that the Asian rice production systems are vulnerable to pest outbreaks (Heong, 2009). Therefore, it is very important to fully understand the status and trends of invertebrate diversity in rice production systems; review the current and potential contribution of invertebrates to these systems including the pest regulatory functions they provide; and identify possible priorities as to their conservation and utilization. Realizing the importance of this issue, the Commission on Genetic Resources for Food and Agriculture of the Food and Agriculture Organization (FAO) of the United Nations requested the International Rice Research Institute (IRRI) to undertake a study with the following objectives:

- understand the status and trends of invertebrate diversity in rice production systems;
- identify areas of knowledge gap in this regard;
- identify the root cause of instability; and
- recommend how stability of rice production systems can be revived.

The target audiences of this study are the governments of rice producing countries, international agricultural development agencies, and national agriculture research, education and extension partners.

The study provides a review of the current and potential contribution of invertebrates to rice production systems. Its findings are essentially based on the review and synthesis of existing literature and data.

II. Invertebrates in rice-based production systems from a historical perspective

II.1. Rice and rice production systems

Rice is the most important food crop in the world with more than half of the world's population eating it as their staple food. It is commonly accepted that Asian rice, *Oryza sativa*, was first domesticated in the Yangtze River valley in China about 8000-10,000 years ago (IRRI Rice Wikipedia). The earliest remains of rice found in the Indo-Gangetic plains of the Indian sub- continent is dated 8000 – 9000 years ago. Asian rice from South and Southeast Asia spread to other regions and countries. In the Middle East, rice was first grown in southern Iraq; and with the rise of Islam, the crop moved north to Nisibin, on the southern shore of the Caspian Sea and then beyond the Muslim world into the Volga Valley. Rice is also grown in the Nile Delta, the Jordan Valley and Yemen. The Moors brought Asian rice to the Iberian Peninsula of Europe in the 10^{th} century, and Muslims introduced it into Sicily. After the 15^{th} century, rice spread throughout Italy, then to France, and was later introduced to all the continents through the European explorers. Rice was one of the earliest crops planted by British settlers in Australia.

Rice was introduced into the Caribbean and Latin America from Asia and Africa by the European colonizers. In 1694, rice arrived in South Carolina, USA probably from Madagascar, and at present, more than 100 varieties are grown in six states of the USA. Californian production is dominated by the *japonica* varieties (Source:

wikipedia.org).

African rice, *Oryza glaberrima,* has been cultivated for 3500 years. Between 1500 and 800 BC, rice cultivation spread from its original center in the Niger River Delta to Senegal. Later, cultivation of the African cultigen declined in favor of Asian rice which was introduced into East Africa from where it spread westwards (Source: wikipedia.org).

The wide dispersal of *O. sativa* and subsequent isolation or selection in Asia has led to the formation of three ecogeographic races: the *indica* race in the tropics and subtropics; *javanica* race in the tropics; and *sinica* (or *japonica*) race in the temperate zone. The races differ in morphological and physiological characteristics, and are partially incompatible in genetic affinity. Of the three races, *indica* is older and the prototype of the other two races. The *sinica* race which differentiated in China, has been rigorously selected for tolerance to cool temperatures, high productivity, and is adapted to the requirements of modern cultivation technology (short plant stature, nitrogen responsiveness, earliness, stiff stems, and high grain yield). The javanica race is of more recent origin and appears intermediate between the other two races in genetic affinity, i.e. it is more cross-fertile with either *indica* or *sinica*.

Currently, rice is grown in all six continents inhabited by humans (Table 1). In 2010, rice was grown in about 154 million ha in 114 countries, and world production was about 672 million tons. About 89% of the world's total rice area is in Asia; 6% in Africa; 4% in South and Central America and the Caribbean; 1% in USA; and less than 1% in Europe and Oceania. The rice lands in Asia produce 90% of the world's rice.

Table 1. World rice area and production by region in 2010

Countries	No. of countries	Area (ha)	Area Share (%)	Production (t)	Production Share (%)
Asia	29	136 550 500	88.87	607 238 408	90.37
Africa	42	9 051 788	5.89	22 855 310	3.40
South America	13	5 090 149	3.31	23 382 492	3.48
Central America & the Caribbean	13	755 392	0.49	2 760 730	0.41
USA	1	1 462 950	0.95	11 027 000	1.64
Europe	11	717 728	0.47	4 443 148	0.66
Oceania	5	23 400	0.02	218 492	0.03
World	**114**	**153 652 007**		**672 015 587**	

Data source: FAOSTAT

Most Asian rice production systems are originally wetlands which were gradually converted into rice fields by man over thousands of years (Kiritani, 2000). Traditional wetland rice production systems were successful: a moderate but stable yield has been maintained for thousands of years without deterioration of the environment (Bray, 1986). This was mainly due to flooding which favors soil fertility and production by: a) bringing soil pH near to neutral; b) increasing the availability of nutrients, especially phosphorous and iron; c) depressing soil organic matter decomposition and thus maintaining soil nitrogen fertility; d) favoring nitrogen fixation; e) depressing outbreaks of soil-borne diseases; f) supplying nutrients from irrigation water; g) depressing weed growth, especially the C-4 types; and h) preventing water percolation and soil erosion (Watanabe et al, 1988).

Due to the differences in describing rice growing environments among the countries and regions, IRRI (1984) realized the need to define the basic rice environments when developing international programs with national organizations. After volumes of correspondence led by an international committee, five basic rice growing environments were proposed, namely: irrigated, rainfed lowland, deepwater, tidal wetlands and upland. However, since data on all five categories are often not available; deepwater rice and tidal wetlands are combined with rainfed lowland rice in this report. Thus in Asia, about 60% of the rice area is irrigated, 34% is rainfed lowland, and 6% upland (Table 2). In Africa; about 20% is irrigated, 49% rainfed lowland, and 31% upland, while in Central and South America and the Caribbean 44% is irrigated and the rest (56%), is rainfed upland. Almost all rice areas in the USA, Europe and Oceania are irrigated.

Table 2. World rice area by environment in 2010

Major region	Total Area (million ha)	Share of Different Environments (%) Upland	Irrigated	Rainfed Lowland
Asia	136.80	5.8	60.4	33.8
Africa	9.09	30.5	20.5	49.0
USA	1.46		100.0	
South and Central America, and Caribbean	5.85	56.0	44.0	
Europe	0.71		100.0	
Oceania	0.02	8.3	91.7	
Total	**153.94**			

Data Source: IRRI GIS

II.2. Diversity of invertebrates in rice production systems

Invertebrates are animals with no vertebral column (backbone) which comprise about 97% of all animals except those belonging to subphylum Vertebrata. Vertebrates such as fishes, amphibians, reptiles, birds and mammals comprise only about 3.0%. In rice ecosystems, the invertebrates are dominated by the arthropods (more than 95%) which are predominantly insects. Invertebrates are involved in diverse functions which include: herbivory (feeding on plants); predation and parasitism of other invertebrates; disease vectoring; pollination; production of silk, honey, lac; and decomposition of plant and animal matter which assists in nutrient cycling.

Assessments of the diversity of invertebrates in traditional rice systems (rainfed rice systems using traditional varieties with minimal external inputs) are scarce. The earliest study on arthropod diversity in rice which used sweep nets for collection was carried out in Japan in 1954-55. The results revealed the presence of 450 species or taxa (Kobayashi et al, 1973) (Table 3). The next attempt was made in traditional deepwater rice in Bangladesh over a three-year period (1977-1980) and collected invertebrates by sweep net and rearing of arthropods. In this study, 369 invertebrates were recorded with 20.5% herbivores, 12.3% predators, 24.6% parasitoids; and 42.6% other species with unknown functions (Catling, 1980) (Table 3). In 1989; IRRI conducted a study of arthropod communities in five sites along an altitude gradient, and found higher species diversity and abundance in the lowlands (Heong et al, 1991). In the 1995 wet season, another study included 57 rice fields in 20 villages under 12 districts in Laos and used D-Vac, Blower- Vac machines and sweep nets three times during the season. It recorded a total of 748 species (Table 3) with 8% detritivores, 31% herbivores, 36% predators and 26% parasitoids (Rapusas et al, 2006).

The arthropods in the traditional deepwater rice system in Bangladesh were less diverse than those in the traditional lowland rice fields in Japan and Laos. This might not only be attributed to the deep flooding in deepwater rice but also to the use of a different sampling method, i.e. a suction machine which can more effectively collect smaller arthropods in the lower plant canopy and on the water surface, was not used in the deepwater rice study.

In traditional rice systems, the diversity of natural enemies was about double that of the herbivores. The herbivore: natural enemy diversity ratio was 1:1.80 and 1:1.96 in Bangladesh and Laos, respectively (Table 3). No studies of invertebrate or arthropod diversity in traditional rice production systems outside of Asia could be found.

Table 3. Diversity of invertebrates in traditional rice production systems in Asia.

Country	Rice Systems	Total Species (No.)	Species Diversity Functional Group	% of Total Species	References
Japan	Traditional	450			Kobayashi et al, 1973
Bangladesh	Traditional deepwater rice	369 (invertebrates)	Herbivores Predators Parasitoids Others*	20.5 12.3 24.6 42.6	Catling, 1980
Laos	Mostly traditional**	748 (arthropods)	Detritivores Herbivores Predators Parasitoids	7.8 31.1 35.6 25.5	Rapusas et al, 2006
Philippines	Traditional and intensive	212			Heong et al, 1991

*Non-pest Coleoptera, Diptera, vagrants and other aquatic groups
** With limited use of nitrogen fertilizer and insecticides

II.3. History of rice ecosystems before the green revolution

Until the late 1960s which was before the start of the RGR, rice production in tropical Asia was based on a low yielding traditional system that relied on rice landraces or cultivars developed by farmers using nominal artificial inputs (Bottrell and Schoenly, 2012). This system was mostly dependent on ecosystem functions and services.

Low external input, traditional organic crop production systems were sufficient for the world population until the early 20th century. But with the increasing demand for food that came with the subsequent population explosion; a serious imbalance between demand and supply occurred, and led to increased pressure for crop production. Thus in the middle of the 20^{th} century; extensive irrigation systems were developed, and external inorganic inputs of fertilizers and pesticides were introduced to increase rice production. Except in Japan, the use of these inorganic inputs was initially low in rice but picked up and intensified during the Green Revolution period.

II.4. Important milestones that have impacted on rice ecosystems

The most important factor to impact on rice ecosystems in Asia was the green revolution which brought about the cultivation of high yielding rice varieties (HYV) with the associated cultural practices of irrigation and application of inorganic fertilizers and pesticides, particularly insecticides. IR8, the 'miracle rice' developed by the International Rice Research Institute (IRRI) with a more than 10 t/ha yield potential, was introduced in 1966 to several countries including the Philippines (Bottrell and Schoenly, 2012) and Bangladesh (then East Pakistan) (Islam and Rabbi, 2002). The RGR was literally and metaphorically a 'technology package' for mass consumption (Settle et al, 1996). The package usually included the HYV seeds, inorganic fertilizers and insecticides, and was supported by overseas development aid programs like Masagana 99 in the Philippines and BIMAS in Indonesia. In many countries, farmers were obliged to use all these inputs which specified calendar-based insecticide applications, often known as "Monday- Monday" or "seven-seven" for weekly insecticide sprays (Van der Fliert, 1993). Although fertilizers usually increase yields and are required for HYVs to reach their potential yield levels (Yoshida, 1981; Huke, 1991), insecticide inputs were based on the unproven assumptions that tropical rice yields are limited by insect pests, and insecticides can control these pests. The then rice-hungry Asia immediately embraced the RGR technologies. IR8 quickly spread throughout tropical and sub-tropical Asia, and contributed significantly in elevating rice production and food security in areas that faced rice shortage (Conway and Toenniessen, 1999). In most countries, almost all agricultural developmental activities were geared to rapid adoption of RGR technology: irrigation facilities were developed, inputs (seeds, fertilizers and insecticides) were made available to farmers at subsidized prices, and agricultural education and extension services were devoted to the RGR. These new technologies quickly replaced traditional rice farming methods in many places (Jennings, 1974). In the Philippines, more than 40% of the rice lands was planted with improved cultivars within 3 years after the release of IR8 (Huke and Huke, 1990). Since then, Asia's efforts were mainly focused on increasing production essentially by replacing traditional rice varieties with high external input dependent RGR varieties, and increasing rice cropping intensity vertically and horizontally.

Asia's RGR almost tripled rice production and averted a potential famine. Production of paddy rice at 232 million tons in 1965 just before the start of the RGR, rose to 672 million tons in 2010 – a 2.9-fold increase. Overall, RGR was a resounding success in expanding food production and improving the livelihood of hundreds of millions of people. From the late 1960s to 1990, rice production growth was strong enough to exceed population growth, thus causing a price decline (Mohanty, 2011) and making rice affordable to the poor segment of the population. The health and nutrition of the Asian people is much better than it was before the Green Revolution. Although the Green Revolution is a success story, there are some unwelcome harvests (Conway and Pretty, 1991). It degraded the environment, the land and the former sustainable production systems through the excessive and/or misuse of fertilizers, pesticides, and irrigation water; it polluted the ground water; and it drastically reduced genetic diversity (Mohanty, 2011).

II.4.1. Rice intensification

The improved rice varieties, especially those developed later by the national agricultural research systems, had relatively shorter growth durations which enabled farmers with irrigation to harvest two to three rice crops per year from the same field (De Datta, 1981). Monocultures of the new high yielding cultivars appeared year-round in many irrigated areas across Asia. Nearly 25% of the rice production growth came from area expansion (Mohanty, 2011) both vertical, i.e. intensification of rice cropping, and horizontal or lateral. Both vertical and lateral expansion of rice area greatly affected biodiversity in the rice production systems by eliminating the fallow period and converting non-cultivated land to rice cultivation. The Asian human population has now reached a stage when it can no longer feed itself without rice intensification, and the options for intensification remain very limited.
In recent years, rice crop intensification has reached a climax in some areas of the Mekong Delta in South Vietnam where farmers are attempting to grow seven rice crops in 2 years. Currently, about 15% of the rice area in six provinces of Vietnam is under such intensive system (Source: Unpublished data from Ho Van Chien, Director, Southern Regional Plant Protection Centre, South Vietnam). In this situation, the question of whether monocrop rice intensification is sustainable or not, arises. The 45 years of painstaking research at IRRI have shown that modern, intensive rice farming is sustainable and can even improve soil health (Pampolino et al, 2008).

Since 1963, IRRI has grown two crops of rice per year at first; then three from 1968 on one hectare of land at its Central Experimental Station at Los Baños in what is known as the Long- Term Continuous Cropping Experiment. Recently, the 145th crop was harvested. The time between harvesting one crop and planting the next (the turn-around time) has been minimal (2 to 3 weeks), and crop residues are removed after harvest instead of being incorporated into the soil because of limited time for decomposition. The results indicate that continuous rice cropping with balanced fertilization on submerged soils actually maintains or slightly increases soil organic matter, and also maintains soil nitrogen. Thus, it is possible to intensively farm rice for a long period using mineral (non-organic) fertilizer without degrading the soil or the land productivity. In fact, soil fertility and production may be improved if the crop is well managed.

The System of Rice Intensification (SRI) was developed by French Jesuit Father Henri de Laularie in Madagascar in early 1980s aimed at increasing the yield of rice in irrigated system without relying on purchased inputs. However, productivity and merits of SRI have been debating over the decades between the supporters and critics. Among the agronomic practices in SRI is the minimal or no use of insecticides. This practice will certainly conserve biodiversity and ecosystem services in rice ecosystems.

II.4.2. Overuse of nitrogen fertilizer

Nitrogen is the most important nutrient for rice production in tropical Asian soils (Kundu and Ladha, 1995). As a rule, one kilogram of nitrogen is required to produce 15-20 kg of rice grain (Bottrell and Schoenly, 2012). Naturally available nitrogen from biological fixation (Ladha et al, 1993) and mineralization of soil nitrogen is enough for yield target of 2.0-3.5 t/ha (Bouldin, 1986; Kundu and Ladha, 1995). In general, a 7 t/ha yield target in a favorable rice season requires 120 kg N/ha whereas a 5 t/ha yield target in an unfavorable season requires 50 kg N/ha (www.KnowledgeBank.irri.org).

Without inorganic fertilizers, the genetically improved varieties yield no better than the traditional varieties (De Datta et al, 1968). In many countries, the government subsidizes nitrogen fertilizers; and farmers tend to overuse nitrogen because of its visible quick effects on plant growth, and ignore its balanced use which makes rice plants vulnerable to certain insect pests and diseases (Islam et al, 2007). Nitrogen-enriched plants can significantly increase the size, performance, and abundance of herbivorous insects (Awmack and Leather, 2002).

Rice plants fertilized with high levels of nitrogen attract more BPH than nitrogen-poor plants, and also improve the insect's survival and reproduction (Sogawa, 1970). Survival of nymphs, fecundity and egg hatchability were significantly higher in BPH populations developed on nitrogen-rich rice plants than on nitrogen-poor rice plants. Feeding on the nitrogen-rich plants allow female adults to survive longer in the absence of food. High levels of plant nitrogen accelerates BPH feeding and honeydew excretion (Sogawa, 1970; Cheng, 1971), survival (Lu and Heong, 2009), fecundity (Visarto et al, 2001; Lu and Heong, 2009; Bottrell and Schoenly, 2012). Field studies have repeatedly demonstrated that BPH populations respond positively to nitrogen fertilization (Cheng, 1971; Dyck et.al, 1979; Heinrichs and Medrano, 1985; Lu and Heong, 2009), and nitrogen fertilizer has been implicated as a major cause of BPH outbreaks in high-yielding systems (Kenmore, 1980; Bottrell and Schoenly, 2012).

Although high levels of nitrogen can boost BPH's reproductive and growth capability, the population often remains small in insecticide-free rice fields receiving high levels of nitrogen (Lu and Heong, 2009). On the other hand, Schoenly et al (2010) and Bottrell and Schoenly (2012) reported relatively high BPH densities in low pesticide (molluscicide only) fields of BPH- resistant rice when high levels of nitrogen (120 kg/ha) were applied. A study at IRRI showed that nitrogen fertilizer favors BPH population growth regardless of the plant resistance level, but the lowest population increase was observed in the plants with higher resistance levels such as that in highly resistant variety IR60 (Heinrichs, 2009).

Table 4 summarizes the recent fertilizer application rates on rice in selected countries. Nitrogen fertilizer application rate is higher than 100 kg/ha in most rice production systems in Asia. China applies almost double (193 kg/ha) than what most tropical farmers usually apply to high yielding rice cultivars (Saleque et al, 2004).

Large planthopper populations and frequent outbreaks in farmers' fields have been reported in hybrid rice (Mew et al, 1988; Sogawa et al, 2003). The dense canopy of the hybrids resulting from more vigorous growth, apparently makes them more attractive to migrating and dispersing insects (Cohen et al, 2003). Hybrid plants have greater nitrogen uptake and nitrogen use efficiency than their inbred parent lines (Virmani, 1994) which may result in more available nitrogen for BPH and other pests (Cohen et al, 2003). The main hybrid rice varieties grown in China are susceptible to white-backed planthopper (WBPH), and only about 12% of the newly developed varieties showed any BPH resistance in field tests (Chen et al, 2005). Since hybrids are grown in more than half of the Chinese rice lands, and rice farmers apply much higher rates of nitrogen fertilizer; populations of BPH and WBPH are likely to remain dangerously high in Chinese rice fields.

II.4.3. Abused use of pesticides

Modern insecticides were introduced to Asian rice in the 1950s but their use was low in the traditional low-input based rice production systems except for Japan. Historically, Japan has been the highest pesticide user in rice. Insecticides were widely applied in Japan before the start of the RGR (Kiritani, 2000). The widespread use of BHC in Japan for controlling rice insect pests especially the striped borer, *Chilo supressalis* during the 1950s and 1960s, induced build-ups of the green rice leafhopper, *Nephotettix cincticeps* due to the disruption of its natural enemies (especially spiders). It also resulted to BHC resistance in *C. suppressalis,* and serious environmental contamination including residues in food and human milk. Concurrently, drastic changes were observed in 1960 in the complex of larval parasitoids of *C. suppressalis* (Kiritani, 1988). Three predominant species of solitary parasitoids were replaced by the braconid, *Apanteles chilonis* when paddy fields in the Aomori Prefecture of northern Japan were treated with pesticides at least once during the cropping season (Toki et al, 1974). Three species of *Sympetrum* dragonflies disappeared almost completely from the same Prefecture (Ueda, 1998). Subsequently, the status of most native economic insect pests and diseases such as *C. suppressalis,* the yellow stem borer, *Scirpophaga incertulas*, *N. cincticeps*; the small brown planthopper, *Laodelphax striatellus*; and two viral diseases vectored by the latter two hopper species, has become less important in Japan. These pests have been replaced by long distance migrants from mainland China: the brown planthopper, the white-backed planthopper and the rice leaf folder, *Cnaphalocrocis medinalis* (Kiritani, 2000). Similar changes have been observed in other fauna of paddy fields, and other native species have decreased in abundance mainly due to the presumed side effects of pesticides.

Table 4. Nitrogen fertilizer use in selected countries in 2001 and 2007

Country	Total Rice Area ('000' ha)	Average Nitrogen Use (kg/ha)	Fertilizer Use (million tons)		
			2001	2007	Increase (%)
Asia and Oceania					
China	29 230	193	6.54	9.17	40.2
India	44 000	100	5.06	6.73	33.0
Indonesia	12 166	96	0.92	1.40	52.2
Bangladesh	11 200	103	1.31	1.47	12.2
Thailand	10 360	25	0.21	0.35	66.7
Philippines	4 250	50	0.27	0.26	- 3.4
Pakistan	2 600	102	0.29	0.32	10.3
Malaysia	660	136			
Iran	630	119			
Africa					
Egypt	668	169	0.11	0.13	18.2
USA and Europe					
USA	1 112	229	0.31	0.35	12.9
EU27	606	76	0.11	0.10	9.0
Russia	189	74			
Turkey	85	141			
South and Central America					
Brazil	2 901	50	0.32	0.44	37.5
Argentina	164	106	0.02	0.02	0
Mexico	71	85			
Chile	27	75			

Source: Gregory et al, 2010

When HYVs were introduced in the late 1960s, insecticides were an important component in the associated package of technologies (Heinrichs, 2009). Insecticide use then picked up rapidly in the rest of the Asia mainly because of the attractive government subsidies, and its promotion as an essential RGR technology for loss prevention from pests. Farmers perceived chemical insecticides as an insurance to protect their investments in fertilizers and other inputs (Bottrell and Schoenly, 2012). Insecticide use particularly spiraled in the high yielding production systems. In the decade before the availability of IR8 (in 1966), about 60% of Philippine farmers used some insecticides; by the late 1970s, nearly 70% of the farmers planting HYV rice routinely applied insecticidal treatments to rice (Kenmore et al, 1987). In the province of Nueva Ecija, Philippines which is a major irrigated rice area, Litsinger (2008) found that farmers treated high yielding rice seedbeds and main crop at an average of 1.4-3.2 times per crop (range 1-10) using 40 different insecticides. Insect epidemics which is ironically often triggered by insecticides, only reinforced the farmers' fear of insect pests and the need to apply more insecticides (Heong et al, 1994; Litsinger, 2008). The farmers continued to treat the rice routinely even though breeders had incorporated insect resistance into the new high yielding cultivars (Heinrichs, 1992; Litsinger, 2009).

As mentioned earlier, the governments of many Asian countries implemented rice production programs (Masagana 99 in the Philippines, BIMAS in Indonesia), and provided subsidies for fertilizer and pesticide inputs (Heong, 2009). In addition, governments and foreign aid projects supported intensive pest surveillance and control programs by considering them as essential inputs. This was true for Japan (Kiritani, 1979), Korea (Turner et al, 1999), Indonesia (Oka, 2003), Malaysia (Triantafillou, 2001), and the surveillance and early warning systems in the Philippines, (Sumangil et al, 1992) and Thailand (Sri Arunotai, 1988). Such 'Fire Brigade' approach which was commonly used in the 1970s, was an unfortunate practice because it did more harm to the pest situation since it created ecological imbalances, polluted the environment and lacked sustainability (Conway, 1997). Since many pest outbreaks occur in small patches, the mass spraying regimes are not only ineffective against pests but they also have a very deleterious effect on non-target organisms.

Today, rice pest management in tropical and sub-tropical Asia is still strongly influenced by the agrochemical era of the 1960s and 1970s. Prophylactic insecticide campaigns are often components of rice production intensification programs, and farmers are encouraged to apply insecticides regularly through the agricultural subsidy and loan schemes (Kenmore et al, 1987). Through its aggressive advertising and marketing campaign, the agrochemical industry also played a role in encouraging pesticide use (Heong and Schoenly, 1998; Islam and Hasan, 1999).

After 30 years of applying insecticides on rice, farmers still have no good evidence that such practice has increased their yields (Settle et al, 1996). In most cases, the use of insecticide either as a preventive or curative control measure was not beneficial (Hasan et al, 2009). Economists have found that productivity gains from insecticide application are doubtful, and productivity is negative when health and environmental costs are factored in (Pingali et al, 1997).

In the past, traditional rice practices used to supply some supplementary food to rural communities, i.e. farmers and the rural poor used to collect vegetables and animal species including fishes from rice fields. Heckman (1979) reported that under traditional rice systems in Thailand, one vegetable and 16 edible animal species (snails, prawns, crabs, large water bugs, fish and frogs) could be collected from a single rice field within one year. Such diversity is less common today because pesticides have rendered these edible species unfit for human consumption (Roger et al, 1991).

II.4.4. Effects of pesticides on invertebrates

Pest outbreaks are sudden explosive increases in a pest population which are often associated with changes in the ecosystem caused by external environmental disturbances. The disturbances include very dry weather, elevated temperatures, floods, gales, and pesticide sprays (Heong, 2009). The application of insecticides to rice fields kills indigenous natural enemies (Kenmore et al, 1987). Insecticides produce the highest negative effects on surface dwelling predators and parasitoids (Settle et al, 1996). Although insecticide applications seek to decrease pest populations, they may also reshape the food web structure (van den Bosch et al, 1982). For example, three applications of deltamethrin caused local pest outbreaks and increased the likelihood of crop damage in an irrigated Philippine rice field (Schoenly et al, 1996). When rice is sprayed at 28-49 days after transplanting, the common natural enemy species become less abundant; and some pests increase nearly fourfold in the sprayed plots over the unsprayed plot. Deltamethrin controlled leafhoppers, seedling midge and whorl maggot, but caused outbreaks of brown planthopper, white-backed planthopper and the planthopper *Sogatodes pusanus*. However, in the sprayed plots; natural enemy populations rebounded following these pest outbreaks (Schoenly et al, 1996). Settle et al (1996) also observed that insecticide applications caused resurgence of brown planthopper.

These and many other experiments clearly show that insecticide applications cause lanthopper outbreaks rather than controlling them. What is the mechanism of such an outcome? In rice, insecticide sprays at the faunal community level usually disturb the predator-prey relationship and the food web structure, thus favoring the occurrence of r-strategist pests (opportunist species which can increase very rapidly under favorable conditions) such as planthoppers (Heong and Schoenly, 1998). In the early crop stages, insecticides are very often either applied as a prophylactic measure or are directed specifically at leaf feeders such as rice leaffolders. Such applications tend to favor the development of secondary pests like planthoppers (Heong, 2009). Outbreaks of secondary pests occur when insecticides are applied to control target pests such as leaffolders, but they also destroy the biodiversity and natural control services, thus rendering the ecosystem vulnerable to pest outbreaks (Heong, 2009). Rice planthoppers are r-strategy opportunist pests whose ecological fitness increases due to the 'release from natural enemies' (Southwood and Comins, 1976). The ecological fitness of the secondary pest species also increases if the crop is enriched with nitrogen fertilizer (Lu et al, 2004). The frequent occurrence of insect pests is a sign of instability in the production environment, and the rapid development of insecticide resistance caused by pesticide abuse is another sign (Heong, 2009).

II.4.5. Loss of rice varietal diversity

In the past, agriculture relied heavily on the genetic diversity of crop plants. During the process of domestication and cultivation of crop plants, a wealth of genetic diversity has been utilized and partly preserved. The quality preferences of rice consumers have also contributed to the wide diversity of varieties specific to different localities. Moreover, socio-cultural traditions have further increased the diversity of rice in terms of morphological and quality traits especially grain size, shape, color, aroma, and endosperm properties (Shiva, 1991). It is estimated that there are around 140,000 different rice genotypes. The IRRI gene bank preserves nearly 100,000 accessions while India alone has 86,330 accessions with 42,000 of them preserved in its national gene bank.

As a central principle of traditional agriculture, plant diversity has contributed to ecological stability, hence to ecosystem productivity. The lower the diversity in an ecosystem, the higher is its vulnerability to pests and diseases, and environmental extremes. From the point of view of yield sustainability, traditional wetland rice cultivation has been extremely successful. But during the RGR, a few high-yielding rice varieties suddenly replaced many traditional land races or cultivars in all major rice production systems. The RGR package has reduced genetic diversity at two levels. First, it replaced mixtures and rotations of crops with monocultures of rice; and second, it replaced hundreds or even thousands of traditional land races and cultivars with a few introduced rice varieties which came from a very narrow genetic base. Thus, the cultivation of a few high-yielding rice varieties across vast landscapes has drastically reduced the former varietal and genetic diversity which led to a perilously small degree of crop diversity. Rice genetic diversity is further reduced by hybrid rice cropping in Asia especially in China where hybrids are grown in more than half of the rice lands. Hybrid rice is being promoted in several Asian major rice producing countries such as Bangladesh, Myanmar, Philippines, and Vietnam.

II.4.6. Impact on invertebrate diversity

Pest management research and development (R and D) in Asian rice in the 1950s to the early 1970s concentrated mainly on pesticides, particularly insecticides. In the 1970s and 1980s, the focus shifted to plant resistance; and since the 1980s, biological control – the use of locallyavailable natural enemies (conservation) and integrated pest management (IPM) were emphasized. Beginning in the 1980s, IRRI investigated the nature of arthropod and invertebrate diversity, i.e. looking at the invertebrate food web structure and dynamics, and the conservation of natural enemies (Kenmore, 1980; Barrion et al, 1994; Schoenly et al, 1998; Islam and Heong, 1999; Schoenly et al, 2010). In 1989, studies using a suction machine at IRRI, Philippines where pesticides use was intensive, revealed only 142 arthropod species (Roger et al, 1991; Barrion et al, 1994; Schoenly et al, 1996) (Table 5).

In a detailed study of arthropod community structure dynamics in rice fields in north and central Java, Settle et al (1996) catalogued 765 species of spiders and insects with roughly 19.0% detritivores and plankton feeders, 16.6% herbivores, 40% predators, and 24.4% parasitoids (Table 5). This study revealed a very diverse natural enemy community in rice. In the late 1990s, in another study on arthropod diversity using a suction machine in two HYV rice production systems in Bangladesh for over six rice seasons, Islam et al (2003) collected 355 arthropod species with roughly 35% herbivores, 33% predators and 32% parasitoids (Table 5). Bambaradeniya et al (2004) reported 494 species of invertebrates in rice in Sri Lanka; while Bang et al (2009) observed 388 species of insects in rice in South Korea. JSAEZ (2006) listed a total of 2275 species of invertebrates in rice environments with 76% insects, 6% spiders and mites, 4% nematodes and 14% crabs. Similar studies of invertebrate diversity have not been conducted in other rice production regions outside Asia.

Table 5. Invertebrate/arthropod diversity in irrigated lowland modern variety rice production systems in Asia

Country	Rice Systems	Total Species (No.)	Species Diversity Functional Group	% of Total Species	References
Philippines (IRRI, Los Baños) (1989)	Irrigated rice (intensive pesticide use)	142 (arthropods)	Herbivores Natural enemies Detritivores	46.2 45.6 8.1	Barrion et al, 1994
Indonesia (North & Central Java)	Irrigated lowland rice	765 (spiders and insects)	Detritivores and Plankton Feeders Herbivores Predators Parasitoids	19.0 16.6 40.0 24.4	Settle et al, 1996
Bangladesh (1999-2001)	Irrigated lowland rice (little or no pesticide use)	355 (arthropods)	Herbivores Predators Parasitoids	34.9 33.2 31.8	Islam et al, 2003
Sri Lanka	Irrigated rice	494 (invertebrates)	Herbivores	26.3	Bambaradeniya et al, 2004
South Korea	Irrigated rice	388 (insects)			Bang et al, 2004
Japan	Irrigated rice	2275 (invertebrates)			JSAEZ, 2006

Researchers have grouped the taxa from rice fields differently. For example, Settle et al (1996) and Rapusas et al (2006) recorded detritivores and plankton feeders as a functional group whereas other authorities did not. Moreover, early studies did not use a suction machine and relied more on the use of the sweep net. Thus, direct comparisons between the field studies are not possible because of differences in sampling methods, sample size, agro-climatic environment, and species grouping. Nevertheless, it is apparent from Tables 3, 5 and 6 that under an intensive pesticide schedule as in the IRRI research farm, invertebrate species diversity is consistently lower (by about a half) than in traditional rice systems, and in modern rice production systems with low insecticide use (Bangladesh and Indonesia).

Within the rice field, the plant canopy supported relatively higher number of *taxa* (202) than the paddy water habitat (180, Schoenly et al, 1998) (Table 7). However, there were nine times more invertebrate individuals in the paddy water.

The number of invertebrate species or taxas and the ratio of total and arable land area of the country showed a positive trend but it was insignificant in a regression analysis. In general, invertebrate diversity in Southeast Asian rice fields (Laos and Indonesia) is probably more diverse than in South Asia (Bangladesh). This may be related to cropping intensity and the extent of non-rice habitats in the rice environments. Natural enemies were more diverse than herbivores (ratio 2:1) in the traditional systems. Intensive pesticide applications significantly reduce invertebrate biodiversity, and shift the ratio between herbivores and natural enemies in favour of the herbivores (1:1).

Table 6. Herbivore and natural enemy diversity in traditional and modern variety rice production systems in Asia

Country	Traditional Rice Production Systems		Modern Variety Rice Production Systems	
	Total Taxa Recorded (No.)	Herbivore: Natural Enemy	Total Taxa Recorded (No.)	Herbivore: Natural Enemy
Bangladesh	369	1:1.8	355	1:1.9
Laos	748	1:2		
Philippines			142	1:1
Indonesia			765	1:3.9

Table 7. Comparison of invertebrate diversity and abundance between the rice canopy and paddy water in a Philippine farmer's irrigated rice field (Data Source: Schoenly et al, 1998)

Parameter	Plant Canopy	Paddy Water
Invertebrate taxa (no.)	202	180
Invertebrate abundance (no.)	9570	84,905
Invertebrate abundance (%)	10	90
Natural enemy's taxa (%)	59	62
Herbivore taxa (%)	30	26
Detritivore taxa (%)	9	11
Tourist taxa (%)	2	1

II.5. Shift in attention after large outbreaks of BPH

II.5.1. Outbreaks during Rice Green Revolution

In mid 1960s, BPH was an unknown pest in tropical Asia. It was not anticipated that BPH would present a serious challenge to the growing of HYV varieties. BPH is an opportunist pest which can develop on cultivated rice and several species of wild *Oryza*. Under favorable conditions and in the absence of natural enemies, it can increase its numbers very rapidly. In the tropics, it can complete 12 generations per year (Dyck et al, 1979). Hundred of years before the RGR, planthopper outbreaks in rice have also occurred in temperate regions notably Japan and Korea (Bottrell and Schoenly, 2012) probably due to a concentration of migrated insects. Planthoppers use wind flow for migration from mainland Asia to Japan. Some kind of specific turbulence in the wind may dump large number of hoppers in small areas causing outbreaks. The most damaging BPH outbreak in the history of Japanese rice production occurred in 1732 which led to famine and caused the death of thousands of people (Heinrichs, 2011).

From the late 1960s until the 1970s, the government of Indonesia contracted stem borer control through aerial applications of insecticides (Mochida, 1978). In 1974, BPH which was never reported as a pest in Indonesia before, emerged in many of the sprayed areas as a pest (Settle et al, 1996) far worse than stem borers (Rubia et al, 1989). The government's response was to promote greater insecticide use. By the late 1970s, huge amounts of rice were lost due to BPH despite increased use of insecticides. The sad irony is that BPH problems are in effect 'self- inflicted wounds' (Settle et al, 1996).

It has now become clear that rice brown planthopper is an insecticide-induced resurgent pest whose degree of damage is positively correlated to insecticide use (Heinrichs, 1979; Kenmore, 1980; Ooi, 1988). Thus, the first response to such widespread outbreaks of brown planthopper, and other pests and diseases, is to develop varietal resistance. IRRI and many national rice institutes, are now engaged in identifying resistant genetic sources in order to develop resistant varieties. The major emphasis is given to planthoppers, green leafhoppers (as vectors of rice tungro disease) and stem borers.

II. 6. Successful case histories

II.6.1. BPH resistance breeding

Anticipating the emerging problem, IRRI started to breed rice varieties for resistance to BPH soon after Pathak et al (1969) identified sources of rice resistance in 1967 (Bottrell and Schoenly, 2012). Many countries in Asia also started similar programs (Settle et al, 1996). The first two resistant genes were designated as *Bph1* and *Bph2* (Athwal et al, 1971); and since then, 21 genes for resistance have been identified from cultivated and wild species of *Oryza* (Brar et al, 2009; Bottrell and Schoenly, 2012).

Producing a durable variety to BPH is a major challenge because of the pest's history of adapting to resistant cultivars (Bottrell and Schoenly, 2012). BPH adapted to IR26, the first high-yielding cultivar with *Bph1* gene, within 2 to 3 years of release to farmers. Other subsequently developed resistant varieties have also remained viable for a relatively short time (Heinrichs 1988). Although some resistant cultivars (IR36 and IR64) have shown greater durability (Cohen et al, 1997), BPH remained a nemesis to plant breeders (Bottrell and Schoenly, 2012). Recent advances in rice genomics offer new opportunities for rice breeders. Breeders can now identify and precisely map the genes for BPH resistance enabling the development of rice cultivars with two or more genes for resistance 'pyramiding' into a single plant which promises greater durability (Brar et al, 2009). In addition, numerous BPH toxins have been identified from non-rice sources with potential in transgenic rice plants engineered specifically to resist BPH (Bottrell and Schoenly, 2012).

II.6.2. International conference in 1977

In response to the threat of BPH outbreaks in the new high-yielding rice cultivars in Indonesia, Thailand, India, Solomon Islands and Philippines,; IRRI convened an international conference in 1977 to review the problem and identify priority research and education programs which would hopefully lead to better management of the pest. The conference emphasized the importance of developing rice cultivars with genetic resistance to BPH while acknowledging that the pest had the capacity to adapt to the resistant cultivars (IRRI, 1979; Bottrell and Schoenly, 2012). The conference also highlighted the need for an integrated pest management (IPM) approach to prevent BPH outbreaks (Bottrell and Schoenly, 2012).

II.6.3. The Indonesian story

In response to the BPH threat, IRRI released seeds of the first BPH resistant variety, IR26 and many Indonesian farmers planted this variety (Settle et al, 1996). However, at the same time; the Indonesian government contracted firms to treat rice fields with insecticides. Within three seasons of the varietal release, BPH successfully damaged rice in most of East and Central Java (Kenmore, 1991). Completely misjudging the situation, the government decided to solve the problem with more applications of insecticides; and in 1975, insecticides were made available to farmers for about 20% of the actual cost (van der Fliert, 1993; Settle et al, 1996). During the early 1980s, however, Indonesian scientists developed and released several new highly resistant varieties which resulted from crossing the resistant variety, IR36 with local germplasm. The BPH problem then subsided for several years, and Indonesia attained the long waited self-sufficiency in rice production in 1984 (Wardhani, 1992; Settle et al, 1996). Two years later came the sudden and dramatic breakdown in the resistance of all these varieties which were all based on IR36 (Kenmore, 1991).

Puzzled by the loss of its rice self-sufficiency; the Indonesian government, at last, took several bold and sensible steps in 1986 (Bottrell and Schoenly, 2012). President Suharto was persuaded to issue a Presidential Decree banning 57 types of insecticides for rice; and 2 years later, the subsidy on insecticides was eliminated (Settle et al, 1996). Since then, IPM became the official approach to pest control. To date, about 500,000 Indonesian rice farmers have been trained for one full season in practical IPM practices (Bottrell and Schoenly, 2012). This training not only reduced the farmers' insecticide use by 60% (Anonymous, 1993) but it also enabled the farmers to have slightly higher yields, higher overall return, and lower production risks (Bottrell and Schoenly, 2012).

II.6.4. FAO IPM inter-country program

With technical assistance from FAO, several countries of tropical Asia launched a major rice IPM program in 1980 to promote sound pest management practices (Gallagher et al, 1994; Matteson et al, 1994; Bottrell and Schoenly, 2012). From 1980 to 1989; the program emphasized pest surveillance, host plant resistance, judicious use of pesticides, natural enemies of pests, and field demonstrations which gave first-hand experience on IPM practices and ecological concepts to farmers (Bottrell and Schoenly, 2012).. The governments of India, the Philippines, and Indonesia declared national IPM policies in the mid 1980s. The policy shift to curb pesticides saved the Indonesian government more than $100 million per year and reduced pesticide imports by two- thirds (Bottrell and Schoenly, 2012).

The FAO-IPM program emphasized intense on-farm training which is well known as 'farmer field schools' (FFS), and made rice farmers proficient in implementing IPM with minimal technical assistance (Bottrell and Schoenly, 2012). From 1980 to 2002, this program trained more than two million farmers in 13 countries, i.e. Bangladesh, Cambodia, China, India, Indonesia, Laos, Malaysia, Myanmar, Nepal, Philippines, Sri Lanka Thailand and Vietnam (Pontius and Barlett, 2011; Bottrell and Schoenly, 2012) and this represents only 1-5% of all farm households in those countries (van den Berg and Jiggins, 2007). The program trained 1.5 million Indonesian rice farmers, where IPM training combined with sensible pesticide policies led to a 75% reduction in insecticide use in Java (Gallagher et al, 1994). Farmers trained in IPM reduced their insecticide use by 50-80% while sustaining or increasing rice yields (Matteson, 2000; Bottrell and Schoenly, 2012).

II.6.5. Farmer participatory research

In 1991, IRRI initiated a complementary pesticide reduction program called 'farmer participatory research' (FPR) to resolve farmers' misperceptions about the need to control rice leaffolders (Bottrell and Schoenly, 2012). Surveys had indicated that most insecticide applications during the first 30-40 days after planting were aimed at leaffolders, while studies showed that leaffolders rarely reduce rice yields if left untreated (Graf et al, 1992; De Kraker, 1996). But rice farmers persisted in their belief that leaffolders would cause heavy losses if not controlled (Heong et al, 1994; Heong and Escalada, 1997).

In the FPR experiments, participating farmers apply their normal insecticide sprays (usually 1-3 sprays) to most of their crop during the first 30-40 days after planting. However, they leave a portion (about 100 m^2) of each field untreated, and at harvest, the farmer determines the yield from both portions of the field and then compares the results with neighboring farmer participants (Bottrell and Schoenly, 2012). Most participating farmers quickly realized the economic benefits of stopping the early treatments and became ambassadors in spreading the 'no-spray' message to other farmers (Bottrell and Schoenly, 2012). In some countries, government agencies initiated complementary media campaigns using radio, TV, printed materials and other means to encourage more farmers to stop early-season use of insecticides (Bottrell and Schoenly, 2012).. The FPR programs in seven locations of Southeast Asia reduced the insecticide use in rice by 50-80% without yield loss (Heong and Escalada, 1997). The greatest impact was in the Mekong Delta of Vietnam, where surveys from 1992 to 1997 showed that Delta farmers reduced the average number of sprays per rice crop from 3.1 to 1.0 (Huan et al, 1999). Throughout the Delta, the FPR programs reduced insecticide use by about 50% on some two million rice farms (Escalada et al, 1999).

II.6.6. International conference of 2008

The first international conference on BPH held at IRRI in 1979 triggered IPM activities, and the need for reducing unnecessary insecticide use and breeding of resistant varieties. This contributed to improved pest management and kept BPH under control for about two decades. In the 1980s and 1990s, FAO and IRRI in collaboration with different national agricultural research and extension systems led in the massive promotion of IPM in rice in Asia. The implementation of the Intercountry Rice IPM program led by FAO during 1980s as well as IRRI's Farmer Participatory Research program in the 1990s, promoted natural biological control in rice ecosystems, and reduced planthopper outbreaks (Kenmore, 1991a; Escalada and Heong, 2004).

Nevertheless, chemical control remained as the main tactic of pest control in tropical Asia (Catindig et al, 2009), and insecticides were still used extensively in Asian countries (Wang et al, 1994; Cheng, 1995). The newly developed insecticide with high efficiency and longer residual period against BPH, imidacloprid was widely used in Vietnam, China, South Korea and Japan from the early 1990s. It seemed that the new insecticide solved the BPH problem (Catindig et al, 2009).

In 2005, serious planthopper outbreaks suddenly appeared in China and were attributed to the development of resistance to imidacloprid and other reasons (Cheng and Zhu, 2006). The planthopper ticking bomb then exploded in 2009 with numerous reports of outbreaks from key Asian rice production areas in Bangladesh, China, India, South Korea, Laos, Malaysia, Philippines, Thailand and Vietnam (Figure 1; Table 8; Heong, 2009a). Data on actual damage or loss were not available. The most significant outbreaks occurred in Thailand, North Vietnam and Yunnan province of China. Rice production in Thailand suffered one of the biggest losses ever experienced. At least 1.1 million tons paddy rice with an export potential value of US$ 275 million was reported lost (Heong, 2009). In North Vietnam, a new virus disease (discovered in China in 2005) called the Southern Rice Black Streak Dwarf Virus and transmitted by the white- backed planthopper, was observed in most provinces in the Red River Delta and spreading to South and Central Vietnam.

Thus, a certain complacency that developed in the 1990s due to the massive IPM efforts and the effectiveness of a new insecticide for BPH was shattered by the new wave of planthopper outbreaks and the emergence of another virus disease (Islam et al, 2009).

As a response to the numerous planthopper outbreaks in China and Vietnam as shown in Figure 1, IRRI convened a second international conference entitled *Planthoppers – New Threats to Sustainability of Intensive Rice Production Systems in Asia* which was held at Los Baños in June 2008. The conference stressed that rice planthopper problems are induced by insecticides, and that the frequent outbreaks are a sign of instability in the production systems due to a breakdown in ecosystem services (Heong, 2009). It also emphasized the shifting paradigms in planthopper management, and charted new sustainable approaches to reestablish ecosystem services that will reduce the vulnerability of farmers' rice fields to hopperburn, virus infections and economic losses.

Table 8. Planthopper outbreaks in Asia's rice production areas in 2009 (Heong, 2009a)

Country	Location/Area
Bangladesh	18 out of 64 districts
China	Yunnan and Guangdong provinces, Hainan Island
India	Punjab, Haryana, Himachal states, no estimate
Korea	Abnormally high abundance observed, no estimate
Laos	Reports of damage but no estimates
Malaysia	Muda area
Philippines	Laguna, no estimate
Thailand	Central Thailand
Vietnam	Mekong Delta, Red River Delta, and Hanoi

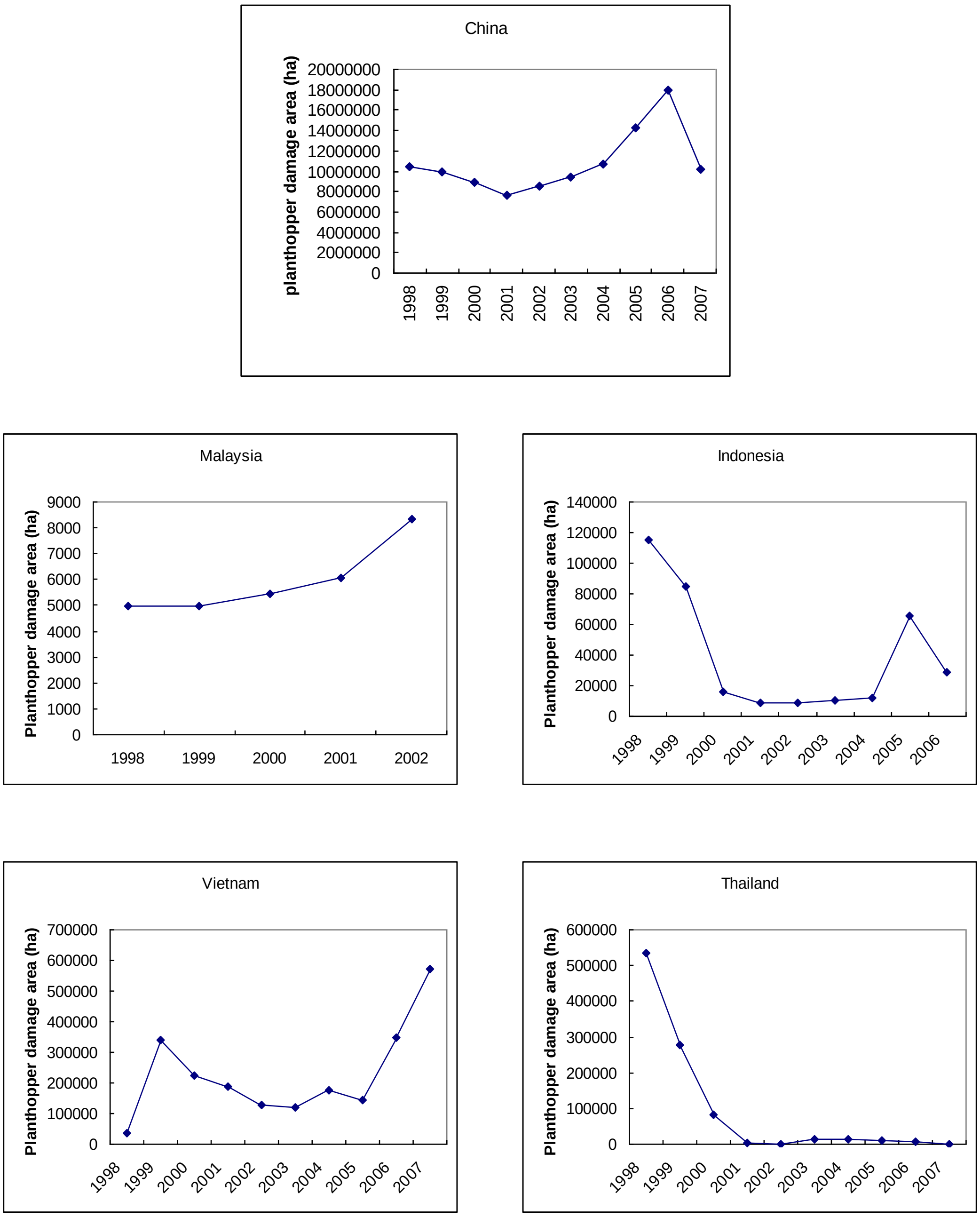

Figure 1. The second wave of planthopper outbreaks in some Asian countries (Catindig et al, 2009)

III. Current understanding of invertebrates in rice systems

III.1. Effects of RGR technologies on invertebrate pest diversity

The green revolution also caused a significant shift in insect pest composition and rank (Table 9; Islam et al, 2009). This is seen most dramatically in the abundance of rice plant-sucking Homoptera, i.e. the near monophagous brown planthopper and most monophagous species of the tropical leafhopper species (Heinrichs, 1994). In general, the new rice technologies boosted the plant sap feeders and those requiring high moisture for their growth, development and survival, but retarded those pests requiring drier conditions and seeking dry soil for pupation. The advent of large areas of irrigated rice retarded population buildups of ear-cutting and swarming caterpillars, mealy bug, grasshoppers and thrips (Table 9). Irrigated rice cropping encouraged caseworms and gall midges while irrigation plus excessive nitrogenous fertilizer favored brown and white-backed planthoppers, green leafhoppers, rice leaffolders and hispa. Rice intensification and greater year-round rice cropping encouraged yellow stem borer and rice bug (Islam et al, 2009).

Increases in the area planted to dry season rice as a result of expanded irrigation have reduced alternate crops and wild grasses which favored specialist monophagous pests such as yellow stem borer but decreased the polyphagous dark-headed stem borer (Lim and Heong, 1977). The white stem borer has decreased in importance because its larvae aestivate in rice stubbles that are destroyed by the dry season land preparation (Heinrichs, 1994). The importance of a major pest of deepwater rice, the rice stem nematode, *Ditylenchus angustus* has declined due to a significant reduction of the deeply flooded crop in favor of HYV rice cropping in the dry season. Such shifts in pest status and abundance took place throughout the major rice growing countries in Asia.

Table 9. Shift of rice insect pest status due to green revolution in Bangladesh (Islam et al, 2009)

Pre-Green Revolution (before 1960s)	Post-Green Revolution (current)
Major Pests	***Major Pests***
1 Ear-cutting caterpillar	1 Stem borers
2 Swarming caterpillar	2 Brown and white-backed planthoppers
3 Stem borers	3 Rice hispa
4 Rice hispa	4 Gall midge
5 Rice bug	5 Rice bug
6 Leafhoppers	6 Rice leaffolders
7 Caseworm	7 Green leafhoppers
8 Mealy bug	
9 Grasshoppers	
Minor Pests	***Minor Pests***
10 Leaf gall fly	8 Ear-cutting caterpillar
11 Rice leaffolder	9 Swarming caterpillar
12 Hairy caterpillar	10 Mealy bug
13 Leaf beetle	11 Whorl maggot
14 Rice thrips	12 Caseworm
15 Rice skipper	13 Long-horned field cricket
16 Rice butterfly	14 Rice thrips

Changes in pest status in Japan were discussed earlier in section II.4.3. The rice water weevil (RWW), *Lissorhoptrus oryzophilus* which has likely invaded Japan from California, was first found in the Chita Peninsula, Aichi Prefecture in 1976. Unlike the bisexual strain found in the southern part of the USA, the Japanese RWW was parthenogenetic like that from California. It became distributed all over Japan by 1986. Thereafter, the RWW invaded Korea in 1988, mainland China in 1988, and Taiwan in 1990. Biological invasion of non-native pests always result in an increase in pesticide application (Kiritani and Morimoto, 2004). Similar changes were also observed in the aquatic fauna of paddy fields. Alien invasive species such as the apple snail, *Pomacea canaliculata* (originating from South America and imported from Taiwan), *and Rana catesbeiana* (imported in 1917 from New Orleans), became common in the paddy fields (Kiritani,2000). Many native species decreased in abundance due to the side effect of pesticide application, and the construction of concrete ditches for irrigation and drainage.

III.2. Ecology of the invertebrate food web in rice production systems

Rice intensification is synonymous with changes in cultural practices such as increases in number of crops grown per year, use of agro-chemicals (fertilizer and pesticides), area under irrigation, and plant densities (Heinrichs, 2011). The essential stable base necessary for assured agricultural production is increasingly being jeopardized by changes in land use, population growth and its demand on the environment, and the threat of climate change (Hawksworth, 1991). At the same time, there is an acute need to increase global food production and to develop a sustainable environment which will indefinitely meet human needs without damaging the environment (Stewart, 1991).

In general, invertebrates play a very important role in agriculture systems which definitely include rice. Invertebrates maintain and promote soil fertility by taking part in the process of organic matter decomposition and soil nutrients recycling, and they are important in the biological control of crop pests. The invertebrates of agricultural production systems including rice, are very diverse. They perform valuable ecosystem functions and provide ecosystem services. In the absence of invertebrates; pest problems would be more severe, and successful crop production would be extremely difficult. However, invertebrate diversity has declined in rice production systems where toxic pesticides have been used.

Pest problems are population problems, a population being a functional unit of the community, which in turn is a component of the environment (Heong, 2009). Therefore, the environment is an important parameter in pest population dynamics. The complex of invertebrates present in rice production systems can be grouped into the following functional groups: detritivores, plankton feeders, herbivores, and natural enemies (predators, parasitoids) for convenience of work and understanding (Settle et al, 1996).

In a study on lowland irrigated rice in Java, Settle et al (1996) showed that arthropod predators enter and remain in rice fields before the pest complex moves into the crop. The predators initially feed on the detritivores and planktonic feeders present in rice fields until such time that the herbivores become more abundant. This finding has changed the traditional concept that the natural enemies closely follow the insect pests after crop establishment. It also helps to explain how natural enemies keep rice insect pests under control. The mechanism of the invertebrate food web in irrigated tropical rice is briefly described below.

Once flooded, tropical rice fields become like a rich “soup” of organic materials originating from the residues of the previous crop, organic wastes brought in by irrigation or rain, flood water from the village, and algal growth (Roger et al, 1991). Bacteria and phytoplankton form the base of the aquatic food web, and are both fed on by zooplankton (Settle et al, 1996) (Figure 2). Populations of small- to intermediate-sized phytoplankton and zooplankton are, in turn, fed on by plankton feeders such as mosquito (*Culicidae*) larvae and true midges (*Chironomidae*) (Settle et al, 1996). Out of the 765 species of spiders and insects collected by Settle et al (1996), roughly 19% species were detritivores and plankton feeders. The true midges (present in thousands m^{-1}) vastly outnumbered the mosquitoes. Ephydrid flies and collembolans are the dominant detritivores present in lowland irrigated rice fields. In the past, the role of the plankton feeders and detritivores in the functioning of tropical rice ecosystem invertebrate food web has been almost entirely unknown or ignored.

Detritivores and plankton-feeding insects provide a consistent and abundant source of food for larger generalist arthropod predators until about halfway through the rice season and before the herbivores including pests, become abundant (Figure 2). Detritivores and plankton feeders reach a peak around 40 days after seeding or 30 days after transplanting, and then decline. By then, the natural enemy population has sufficiently built up to exploit the herbivores and keep them under control or at low levels for rest of the season, unless insecticide application disrupts the balance. The parasitoids probably follow the pest populations more closely.

Hidaka (1990) observed an immigration of spiders into the paddy fields after the appearance of chironomids. If chironomids are abundant, the density of spiders increases correspondingly, and they then act as a biological control agent against planthoppers and leafhoppers. The collembolans, *Akaboshia matsudoensis* and *Homidia* sp. reach very high densities in the late season when insecticide application is less frequent. These collembolans are mycophagous, feeding on spores and hyphae of the blast fungus, *Pyricularia oryzae*, and sheath blight fungus, *Rhizoctonia solani*. The larvae of the firefly, *Luciola lateralis*, and larvae of dragonflies act as efficient predators of juvenile apple snails, *Pomacea canaliculata* (Kondo and Tanaka, 1989; Suzuki et al, 1999).

The invertebrate food web in tropical irrigated rice is exceedingly complex. Most insect herbivores co-vary with the large complex of natural enemy species through a rich and intricate web of predators, parasitoids, parasites and detritivores which live in the plant canopy, on the water surface, in paddy water, and on or in the water-logged soil (Schoenly et al, 1998). Biological control in these agroecosystems involves many species, spans multiple trophic levels and acts along spatiotemporal gradients (Schoenly et al, 1998). In the real world, there are many links and interlinks between species of different functional groups.

The basic links between the functional groups of the food web are shown in Figure 3. This is a simplified version of the complex food web which highlights that rice fields are not closed systems. They are open systems where linkages extend across the field boundaries to adjacent fields, and non-rice habitats such as bunds, irrigation canals, nearby fallow areas or fields, ponds, and the vegetation present in these habitats. These non-rice habitats provide shelter and supplementary or alternate food to the natural enemies. Provision of such functions is necessary to maximize ecosystem regulatory services at difficult times such as at tillage and after crop harvest. These biocontrol linkages can easily be disrupted by broad spectrum insecticide applications (Heong et al, 1991; Cohen et al, 1994; Settle et al, 1996; Schoenly et al, 1998,) and bring economic, health, and ecological costs to the farmer (Pingali and Roger, 1995; Schoenly et al, 1996a; Heong and Schoenly, 1998).

Natural enemies are not only confined to rice fields. Predators such as crickets and many parasitoids live in the non-rice habitats and visit rice fields in search of prey or hosts. This non- rice vegetation plays a commanding role in diversity and maintaining a balance in the system.

The life cycles of many aquatic organisms depends in part on the rice field (Kiritani, 2012). For example, nine out of 14 species of frogs native to Japan use paddy fields for oviposition (Hasegawa, 1998). Likewise, the *Odonata* utilizes paddy fields for oviposition (Ueda, 1998). Many of the aquatic hemipteran and coleopteran insects including the giant water bug, *Lethocerus deyrollei*, water scorpions, *Laccotrephes japonensis* and *Ranatra chinensis*, Dytiscid beetles, Hydrophilid beetles, and fire flies, are known to reproduce in paddy fields (Kiritani, 2012). Many arthropods with diverse life cycles occupy different habitats within the paddy ecosystem. In Japan, *Symptrum* dragonflies emerge from paddy fields and migrate to secondary forests where they remain until sexual maturation. They then return to paddy fields to deposit their eggs which hatch in the following spring when irrigation water becomes available. Newly emerged adults of the water scorpion, *Tanatra chinensis,* immigrate from paddy fields to irrigation ponds where they overwinter in the bottom mud before oviposition takes place in the paddy field in the spring (Hibi et al, 1998).

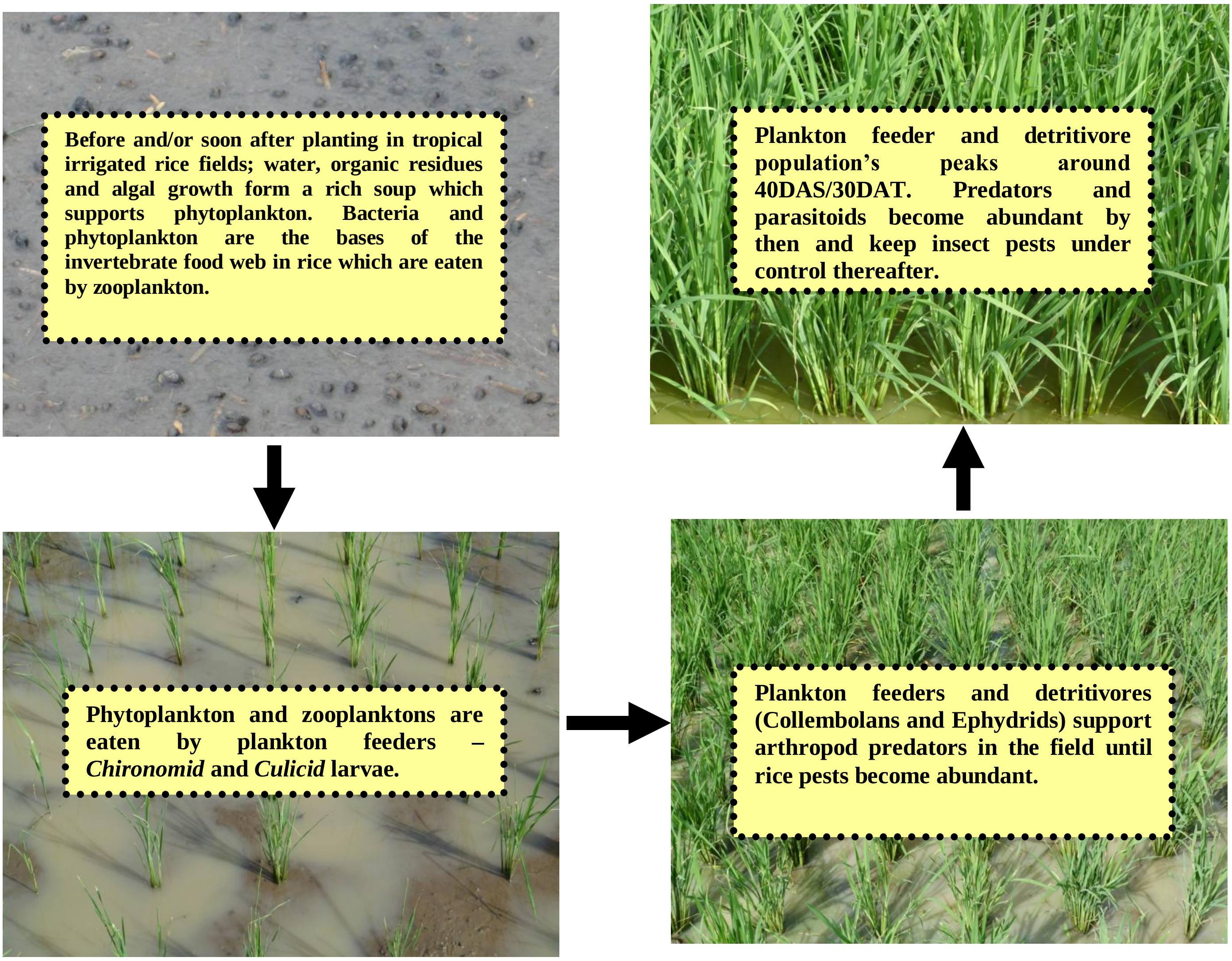

Figure 2. Mechanism of invertebrate food web functioning in tropical irrigated rice (DAS = days after seeding; DAT = days after transplanting). (Adapted from Settle et al, 1996)

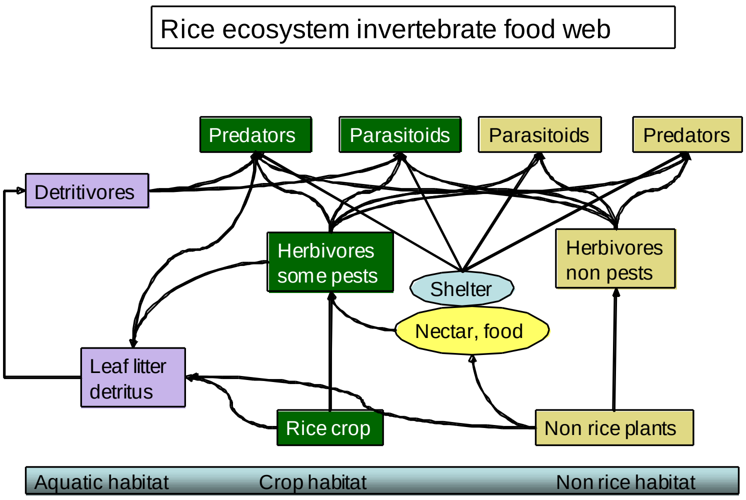

Figure 3. Invertebrate food web in rice ecosystem (After K.L. Heong, IRRI)

III.3. Status and trends in biological control agents in rice ecosystems

The biological control system is very complex mainly because of the sheer numbers of prey and natural enemy species involved, and because predators are generalist feeders, i.e. one predator species attacks many host species. Predatory behavior is widespread among insects, spiders and mites. More than 40 families of insect predators play a significant role in suppressing agricultural and forestry pests. The most commonly found families of insect predators in field crops are: *Reduviidae*, *Gerridae* (pond-skaters), *Vellidae*, *Miridae*, *Anthocoridae*, *Pentatomidae* (all Hemiptera or plant bugs); *Chrysopidae* (green lacewings) (Neuroptera); *Carabidae* (ground beetles), *Dytiscidae*, *Staphylinidae* (rove beetles), *Coccinellidae* (lady bird beetles); *Formicidae* (ants) (Hymenoptera); *Cecidomyiidae*, *Syrphidae* (Diptera or flies). Virtually all of the 60 families of spiders (*Araneae*) are predators. Of the 27 or more families of mites (*Acari*) that prey on or parasitize other invertebrates, eight are significant for biological control (Islam and Catling, 2012).

The sheer complexity of the natural enemy complex is evident by looking at the species known to attack just one major pest of rice in Bangladesh – the yellow stem borer (Table 10). There are six parasitoids (belonging to four families) attacking the eggs of the borer, and nine parasitoids (from seven families) attacking the larvae. In addition, there are 18 predator species (13 insects belonging to six different orders, and five spiders).

III.3.1. Classical biological control of rice pests

The first example of classical biological control is the successful control of the cottony cushion scale, *Icerya purchasi* Maskell, of citrus in California by the introduction of the *Vedalia* beetle, *Rodalia cardinalis* (Mulsant) from Australia in 1888-89. Since then, more than 5000 programs for releasing exotic insect control agents, and more than 200 insect pests have been either completely or partially controlled. The highest success rates have been against Homopteran insects, i.e. aphids, planthoppers, scale insects and mealy bugs (Greathead, 1995).

Table 10. Parasitoids and predators attacking yellow stem borer in deepwater rice in Bangladesh

Parasitoids	**Stage Attacked**	**Predators**	**Stage Attacked**
Telenomus rowani (Gahan)	Egg	*Conocephalus longipennis* (de Haan)	Egg
Tetrastichus schoenobii Ferriere	Egg	*Euscyrtus concinnus* de Haan	Egg
Trichogramma japonicum Ashmead	Egg	*Tetragnatha javana* (Thorell)	Adult
Trichogramma pallidiventris Nagaraja	Egg	*Tetragnatha vermiformis* (Emerton)	Adult
Telenomus sp.	Egg	*Lycosa annandalei* Gravely	Adult
Eupteromalus parnarae Gahan	Egg	*Clubiona japonica* Boesenberg et Strand	Adult
Shirakia schoenobii Viereck	Egg	*Clubiona* sp.	Adult
Cotesia flavipes Cameron	Larva	*Agriocnemia pygmaea* (Rambur)	Adult
Exoryza schoenobii (Wilkinson)	Larva	*Ceriagrion coromandelianum* (F.)	Adult
Temelucha stangli (Ashmead) *T*	Larva	*Ishura aurora* Brauer	Adult
emelucha philippensis (Ashmead)	Larva	*Ophionea indica* (Thunberg)	Egg, pupa
Chelonus nr munakatae Munakata	Larva	*Paederus fuscipes* Curtis	Egg, pupa
Isotima javensis Rohwer	Larva	*Micraspis discolor* (F.)	Egg
Amauromorpha sp.	Larva	*Orius tantillus* (Motsch.)	Egg, larva
Mermithid nematode	Larva	*Chlaenius* spp.	Larva, pupa
		Monomorium latinoda Meyr.	Egg, larva
		Pheidole megacephala F.	Egg, larva
		Labidura riparia (Pallas)	Egg, larva

Directed attempts at the biological control of rice insect pests are relatively a recent development. Only two rather insignificant cases are known where the introduction of exotic parasitoids was relatively successful to control a rice pest. In 1928, populations of the immigrant rice leaffolder, *Marasmia exigua* in the Fiji Islands were apparently reduced by the introduction of *Trathala flavoorbitalis* (Cameron) (*Ichneumonidae*) from Hawaii (Ooi and Shepard, 1994). In the 1930s, three parasitoids introduced from Asia helped to reduce infestations of the rice striped stem borer, *Chilo suppressalis* in Hawaii. Several other attempts to introduce exotic parasitoids against indigenous rice insect pests in South and Southeast Asia were unsuccessful. Such interventions are costly with uncertain effectiveness, and do not appear to be an economic proposition in annual crops such as rice (Islam and Catling, 2012).

III.3.2. Conservation biological control of rice pests

The biological control of rice pests has traditionally been sustained through the conservation of invertebrates in the rice fields. This stable traditional ‘natural biological control’ system which relies on the conservation of natural enemies, has persisted for thousands of years. It was the RGR technologies, a recent phenomenon, which disrupted this natural balance through the application of modern insecticides (Heong and Schoenly, 1998), switching to rice monocultures and practicing clean cultivation. After experiencing four decades of pest

outbreaks beginning in the 1970s, and using several different approaches to pest control (particularly chemical control and plant resistance), researchers now realize that the conservation of natural enemies in the rice agroecosystem to maintain the natural faunal balance, is crucial in avoiding serious pest outbreaks.
There is overwhelming evidence that the severe disruption of the natural enemy complex by the application of broad-spectrum insecticides has frequently led to pest resurgences in rice paddies. During the early growth stages of the rice crop, abundant populations of detritus- and plankton- feeding insects such as *Collembola* support large numbers of generalist predators (Settle et al, 1996). This alternative prey gives the predators a head start in preventing pest buildups. The conservation of natural enemies is clearly the best strategy in field crops of short duration such as rice.

Several practices which are crucial in conserving and exploiting the activities of the natural enemies in rice agroecosystems are listed as follows:

- Avoiding the misuse of insecticides: by following judicious use principles, using pesticides only where and when necessary;
- Managing the vegetation on rice bunds and in adjoining non-rice habitats: maintaining nonrice vegetation in the ecosystem;
- Incorporating crop mosaics, staggered planting, and growing some non-rice crops: avoiding strict synchronous planting;
- Avoiding disruptive cultural practices: not burning rice stubble spread over the field; and avoiding puddling by tractors;
- Encouraging vertebrate predators such as frogs, ducks, fishes and insect predatory birds such as the black *drongo* which is common in South Asia.

III.3.3. Ecological engineering

Ecological engineering has recently emerged as a strategy for considering pest management approaches that are based on cultural practices and ecological information rather than on high technology approaches such as synthetic pesticides and genetically engineered crops (Gurr et al,2004). It is a human activity which modifies the environment according to ecological principles. Accordingly, it is a useful conceptual framework for considering the practice of habitat manipulation for arthropod pest management. The term ‘ecological engineering’ was first used by Odum (1962) to refer to ‘environmental manipulation by man using small amounts of supplementary energy to control systems in which the main energy drives are still coming from natural resources’ (Gurr, 2009). The concept has evolved to ‘the provision of guidance and methodologies for systematic, intelligent design of ecological system for the benefit of humans and nature’. Characteristics of this approach are a) low dependence on external and synthetic inputs, b) reliance on natural processes, c) based on ecological principles, and d) scope for refinement by ecological experimentation.

The Millennium Ecosystem Assessment (MA, 2005) convened by the United Nations adopted the ecosystem services framework to broadly consider human and ecological interactions. The ecosystem basically provides four broad types of services, namely: provisioning, supporting, regulating, and cultural services**.** The provisioning services include the production of food, fresh water, fuel, wood and fiber. The supporting services provide for maintenance of the resource base and include nutrient cycling, soil formation and primary production. Regulating services include water purification, climate and flood regulation and pest regulation, while cultural services provide humans with aesthetic and spiritual values, education, and recreation (Figure 4).

Biodiversity is the foundation of ecosystem services contributing to all four types of services. Biodiversity through ecosystem functions contributes directly to sustainable agriculture through pollination, pest invasion resistance, natural biological control, and pest and disease regulation (Heong, 2009).

Natural biological control is linked to pest regulation and invasion resistance services, and their importance was strongly emphasized more than 30 years ago by Bosch et al (1973). The important role of biodiversity in rice was also discussed by Way and Heong (1994). In 1973, Bosch et al pointed out that chemical-based pest management has three ecological backlashes namely: target pest resurgence, secondary pest outbreaks, and pesticide resistance. Such phenomena have always been observed in rice production systems (Heong, 2009). Studies at IRRI in the early 1990s indicated that the quantity and quality of egg parasitoids in rice fields could be enhanced by regulating the proportion of vegetation and arthropods in the surrounding nonrice habitats (Xiaoping et al, 1996).

Ecological engineering methods are influencing recent developments in enhancing the biological control of rice insect pests. Ecological engineering is a form of conservation which offers shelter and supplementary and/or complementary food for natural enemies. Here, deliberate attempts are made to halt unnecessary insecticide applications, and to attract parasitoids by planting nectar- rich flowering plants like sesame, on the rice bunds. Currently; China, Vietnam and Thailand in collaboration with IRRI, are pioneering ecological engineering experiments, and improvement of methods through the mass media (Gurr et al, 2012).

Provisioning Products for the ecosystem	**Regulating** Benefits from regulation of ecosystem processes	**Cultural** Nonmaterial benefits from ecosystems
In most lowland rice • Nitrogen fixing • Food production	• Water regulation Food storage • Climate regulation Raise local humidity Anaerobic soils store C	• Spiritual and religious values • Cultural heritage
Lowland under specific management • Food (rice) production, nonrice crops, fish • Wood and straw for fuel • Genetic resources, wild rice	• Water regulation Soil salinity management • Climate regulation • Purification of polluted water • Soil organic matter maintenance • Biological control – pest and disease regulation • Pest invasion resistance	• Aesthetic • Inspirational • Educational • Recreation and ecotourism
Supporting Services Services necessary for the production of all other ecosystem services include soil formation, nutrient cycling, and primary production. These services depend heavily on connectivity/flows between rice fields and surrounding habitats.		

Figure 4. Ecosystem services of lowland rice (Heong, 2009)

III.4. Impact of different practices on invertebrates

In general; the use of organic matter, mulch and green manure, less tillage and flooding, crop rotation, organic agriculture and fertilization positively influence the soil invertebrates (Brown et al, 2001). On the other hand; pesticides, frequent and deep tillage, burning, monoculture, fumigation/solarization, compaction and contamination negatively affect the soil biota.

Brown et al (2001) observed that no-tillage systems provide the ideal environment for the reestablishment of ecosystem 'engineers' such as earthworms; scarab beetle larvae; saprophagous and litter transforming invertebrates (termites and millipedes); and soil-living predators (pseudoscorpions, centipedes, *Diplura* and spiders). All of them help in enhancing the system's natural biological control activity.

Aside from the effect of insecticide applications, the impact of the various cultural practices on rice invertebrates has drawn very little research attention. Pesticides, particularly insecticides which have been covered elsewhere in this report are probably the most destructive to rice soil invertebrates. Natural enemies are particularly vulnerable to insecticide applications because of their vigorous prey/host searching behavior.

Other cultural practices that seriously disrupt invertebrate populations include the burning of rice stubbles, straw and rice husks when spread over the field; the trimming of non-rice vegetation from rice bunds prior to tillage (puddling) (Islam and Heong, 1999); destruction of field vegetation during fallow periods; and strict synchronous rice planting over large areas (Islam and Catling, 2012). Puddling (tillage of flooded fields) disturbs natural enemy populations developing during the fallow period. It is better to incorporate crop residues into the soil rather than burn them. If burning is essential, the residues should be burned in heaps and not over the whole field.

III.4.1. Impact of fallowing

Schoenly et al (2010) studied the effect of fallowing on the invertebrate fauna during the dry season at two sites in the Philippines in 1992 and 1993. Fallowing did not affect the community structure, trajectories, and accumulation rate of guild numbers of the rice-invertebrates between seasons. Results also indicated that small-scale synchronous fallowing when included in asynchronous planted landscape, does little harm to the biological regulation of the invertebrate faunal community, and may be adopted as part of IPM (Schoenly et al, 2010).

III.4.2. Impact of crop intensification

A climax community is a biological community of plants and animals which has reached a steady state through the process of ecological succession (the development of vegetation in an area over time). This equilibrium occurs because the climax community is composed of species best adapted to average conditions in that area. Traditional rice fields, some of which have been cultivated for several hundred years, may be considered as climax communities (Roger et al, 1991).

In general, any disturbance to a stabilized ecosystem reduces the number of species while provoking 'blooms' of certain others; and such effects have been observed in rice fields (Roger and Kurihara, 1988). The RGR technologies which utilize fertilizer-responsive varieties, fertilizers, pesticides, optimum water and other associated crop management practices, have tremendously increased grain yields and production but have also greatly modified the traditional rice-growing environments (Roger et al, 1991).

Quantitative knowledge of the long-term effects of crop intensification on species diversity is very limited. It was noted earlier that only three references on species diversity in traditional rice systems are available. Moreover, the traditional rice and HYV production systems could not strictly be compared primarily because of differences in sampling methods and species diversity (Tables 3 and 5). However, there is some indication of significant reduction in invertebrate diversity under intensive insecticide applications. Consequently, this also increases herbivore diversity, and shifts the herbivore and natural enemy ratio in favor of herbivores.

III.4.3. Impact of land changes

The rice ecosystem consists of two physically and morphologically distinct habitats which are the fields comprising mainly of the rice plants, and the surrounding bunds (levees) which harbor weeds. Under irrigated conditions, this mosaic system is connected with irrigation canals and ditches while in some areas; swamps, ponds, marshes and tanks serve as contiguous aquatic habitats. Structural changes made for irrigated rice have reduced or affected the non-rice habitats in the rice ecosystems.

Increases in Asian rice production have been achieved by applying either environment-adaptive and /or environment-formative technologies (Tanaka, 1995). The former involves agronomic technologies while the latter refers to the development of infrastructures for rice cultivation. Conversion of ill-drained paddy fields into well-drained dry ones was promoted by the Japanese Government in order to raise both land and labor productivity. Traditional earth ditches were replaced by U-shaped concrete ditches, and the distributive canals were then separated from drainage canals. This effectively reduced the variety of habitats for fishes and limited their movement within the paddy water system (Fujioka and Lane, 1997). As a result of these changes to the land; the insects, *L. deyrollei* (Hemiptera: *Lethocerinae*) and *Cybister tripunctqatus orientalis* (Coleoptera: *Ditiscidae*), five bird species, one fish, one amphibian, and three plant species are now listed in the IUCN Red List as endangered species inhabiting paddy fields (Hidaka, 1998).

III.4.4. Impact of synchronous and asynchronous planting

Different views have been expressed on whether synchronous or asynchronous planting maintains lower pest densities throughout the year in tropical rice landscapes (Dyck et al, 1979; Oka, 1988; Loevinsohn et al, 1993; Way and Heong 1994; Settle et al, 1996; Schoenly et al, 2010). Historically, policy makers have recommended wide-scale synchronous planting to deprive rice pests’ food and refuge into which they can invade after planting (Bottrell and Schoenly, 2012). Synchronous cropping which creates a rice-free fallow period lasting 1-3 months is widespread due to the need to conserve water in the dry season. It allegedly promotes rapid population buildups of the BPH and green leafhopper in the post-fallow, wet season crops (Widiarta et al, 1990). Moreover, it may also produce more frequent and intense pest outbreaks due to smaller and less diverse predator populations than asynchronous crops (Sawada et al, 1992; Wada and Nik, 1992; Settle et al, 1996). Therefore, Bottrell and Schoenly (2012) speculated that prolonged and dry fallowing between cropping seasons can deplete natural enemy populations, and reduce their effectiveness to control pests in subsequent (post-fallow) crops.

On the other hand, asynchronous cropping creates a heterogeneous mixture of cultivated and temporarily unused fields, and is common where irrigation systems are less efficient or have slower water delivery rates (Litsinger, 2008). Fallowing reportedly disrupts insect pest life cycles (Dyck et al, 1979; Oka, 1988; Loevinsohn et al, 1993) and reduces leafhopper-transmitted diseases (Wada and Nik, 1992; Cabunagan et al, 2001). Asynchronous cropping creates continuous refuges for migrating arthropods. However, its spread over large areas results in less efficient use of irrigation water (Loevinsohn et al, 1993; Litsinger, 2008) and may increase problems with rice rats (Lam, 1983), birds (Islam and Catling, 2012) and *tungro* virus (Wada and Nik, 1992; Bottrell and Schoenly, 2012).

The original metapopulation model (a metapopulation consists of a group of spatially separated populations of the same species which interacts at some level) of Levins (1969) and later versions (e.g. Hanski, 1991) provide theoretical support for the synchronous rice cropping system (Bottrell and Schoenly, 2012). This is because the persistence of a metapopulation requires asynchronous dynamics of local genetically connected populations (Hanski, 1999). The Levins (1969) and subsequent metapopulation models ignored the role of migrating natural enemies in pest outbreaks (Jervis, 1997; Bottrell and Schoenly, 2012). After incorporating both natural enemies and pest movements in their metapopulation model; Ives and Settle (1997) found that the asynchronous crop with the predators migrating between fields, lowered pest densities more than the synchronous crop without migrating predators. They also observed reduction in pest populations if the predators move into the field early and exploit the natural prey (Bottrell and Schoenly, 2012). The theoretical and empirical studies suggested that heterogeneous landscapes allow mobile generalists and many insect parasitoids in rice in tropical Asia to increase rapidly in response to increasing pest abundance (i.e. “birdfeeder effect”), and that this plays a key role in stabilizing food webs (Kondoh, 2003; McCann et al, 2005).

In agroecosystems; the birdfeeder effect can be triggered by farmer intervention which encourages pest outbreaks (Bottrell and Schoenly, 2012). For example; farmers in Zaragoza, Philippines have been forced to adopt asynchronous planting due to uncertain irrigation water (Loevinsohn et al, 1993). Outbreaks of BPH, WBPH and another delphacid species occurred at this site after the application of deltamethrin. During the 21-day spray interval; the predator population was greatly reduced, then rebounded to the sprayed field, and eventually outnumbered the predators in the unsprayed plot (Schoenly et al, 1996).

III.4.5. Impact of tillage

Literature on the effect of tillage on rice invertebrates is scanty. However, one study at IRRI by Islam and Heong in 1999 produced interesting results. Although 30-cm wide rice bunds are usually narrow, they served as a rich faunal reservoir, and supported an average of about 800 invertebrates m-1 (Table 11). About 28% of these invertebrates were herbivores, 36% were predators, and another 36% were detritivores.

Tillage (puddling) drastically reduced the numbers in the field from 387 m-1 to 113 m-1 (71% reduction). During tillage operations; some arthropods took refuge on the bunds, and others probably moved beyond the bunds and into other rice fallows. The effect of tillage was most severe on herbivores (93% reduction), followed by predatory insects (84% reduction), and detritivores and others (43% reduction). Bunds with lush vegetation accommodated more invertebrates than those where vegetation was trimmed. During fallow periods and tillage operations, rice bunds are clearly an important habitat and refuge point. Management of vegetation on the rice bunds appears to be an important measure for the conservation of natural enemies, especially at the beginning of the rice season.

Table 11. Effect of tillage on invertebrates in rice fallow fields and bunds

Invertebrate Group	Fallow Rice Field (no. m-1)		Rice Bunds (no. m-1)		
	Before Tillage	After Tillage	Before Field Tillage	After Field Tillage	
				Vegetation Trimmed	Vegetation Untrimmed
Herbivores	89	7	247	152	172
Predators	155	25	272	198	348
Detritivores and others	143	81	281	524	1539
Total	387	113	790	874	2059

(Data Source: Islam and Heong, 1999)

III.4.6. Impact of aerobic and anaerobic seeding

Rice is grown mostly under anaerobic conditions in irrigated and rainfed lowland environments. Since most studies have been carried out in Asian rice fields that were flooded for most of the season, the effect of anaerobic conditions on the invertebrates is quite well known. However, rice is mostly grown under aerobic conditions in the uplands, dryland and hilly areas where very little data on invertebrate diversity and food web are available.

III.4.7. Impact of irrigation

The effect of irrigated rice cropping on invertebrate pests was already discussed in section III.1; but there has been little investigation about the effect of irrigation on invertebrate food webs, diversity and abundance. As cited earlier, Schoenly et al, (1998) found 180 taxa in the paddy water and 202 taxa in the rice crop canopy, but invertebrates were far more numerous in the paddy water (90%) than in the plant canopy (10%). Thus; it appears that irrigation greatly increases invertebrate diversity and abundance. The effects of intermittent irrigation (wet followed by dry) which will likely become a dominant practice in the future because of water scarcity, has not drawn any research attention. Alternate wetting and drying may affect the diversity and abundance of aquatic invertebrates which may also influence the biological control of rice pests.

III.4.8. Impact of fertilizer application

There is useful literature on the effects of nitrogen fertilizer on insect pests such as planthoppers, but data on the effects of nitrogen on the other functional groups of invertebrates, and the influence of other fertilizer types are very limited.

The use of inorganic fertilizers especially nitrogen, and its effects on rice pests have been discussed in some detail in section II.4.2. During the RGR period, inorganic fertilizers became the trademark feature of the high-yielding rice cultivars. In general, increased plant nitrogen accelerates the feeding and honeydew excretion, survival, fecundity and population growth of BPH; and thus, can induce outbreaks. At the IRRI farm in the Philippines, population densities of *Limnodrilus hoffmeisteri* and *Branchiura sowerbyi* (oligochaetes, annelids) were correlated with moisture, soil organic matter and the amount of nitrogen applied (Simpson, 1992). In Indonesia, the level of organic matter influenced the populations of invertebrate predators in rice fields (Settle et al, 1996). Plots with high levels of organic matter supported higher populations of predators (both below and above the water) than plots with low organic matter.

III.4.9. Impact of pesticide application

Invertebrates which are either living in or near the rice fields, are affected by pesticide application whose effects may be lethal, sub-lethal or both. Herbicides can have a significant indirect effect by removing the food plants of many invertebrates. Some general effects of insecticides on soil- inhabiting and aquatic invertebrates are summarized in Table 12.

Studies on pesticide effects on paddy water populations show that insecticides are usually the most active compounds (Roger et al, 1991). Insecticide application usually causes a general decrease in paddy water invertebrates followed by proliferation of primary consumers particularly ostracods, chirominid and mosquito larvae, and mollusks (Ishibashi and Ito, 1981; Roger and Kurihara, 1988). Ostracods rapidly recover because of their resistance to pesticides and their ability to produce large number of eggs parthenogenetically. Populations of predators such as Odonata larvae are also reduced by insecticides (Takamura and Yasuno, 1986). Applications of benthiocarb had no marked effect on the number of nematode species and their average population size (Ishibashi and Ito, 1981). However, a 70% reduction in soil oligochaete populations was recorded when the rate of Furadan was increased from 0.1 to 1.5 kg a.i.ha-1.

Table 12. Some general effects of insecticides on soil-inhabiting and aquatic invertebrates (After Edwards, 2000a)

Taxon	Comments
Soil-Inhabiting Invertebrates	
Nematoda	Not susceptible to most insecticides but individual effects can occur leading to changes in community composition. Some insecticides can also have a nematicide action, e.g. carbofuran
Acarina	Great variation in susceptibility with active predatory species often more susceptible than sluggish saprophagous species.
Collembola	Susceptible to many insecticides but some aspects not well documented and difficult to predict. As with insects, strong positive correlations between activity and susceptibility have been reported.
Pauropoda	Seem to be extremely sensitive to many insecticides
Symphyla	Apparently not very susceptible; repelled by insecticides and can reduce exposure by deep burrowing
Diplopoda	Intermediate in susceptibility between pauropods and symphylans; increased susceptibility when on soil surface due to greater exposure.
Chilopoda	Tend to very susceptible; deletion made because of high activity as predators; relatively sensitive to many insecticides
Oligochaeta: Lumbricidae Mollusca	Other than methiocarb, insecticides are not toxic to snails and slugs, probably because the mucous coating is protective. Some insecticides can accumulate in mollusk tissues which can then affect predators such as birds and people eating snails.
Insecta	Very difficult to generalize; great variations in susceptibility
Aquatic invertebrates	
Mollusca, Oligochaeta	Benthic fauna of these groups appear to have lower susceptibility to insecticides than aquatic arthropods but can bioaccumulate some insecticides
Crustacea	All seem to be relatively more susceptible to most insecticides, with incidence of large-scale kills from spraying or spillages.
Insecta	Most aquatic insect larvae are very susceptible to insecticides

Insecticides can also promote pest increase via hormesis (favorable biological response to low exposure to toxins and other stressers thus, opposite effects in small doses than large doses) (Hardin et al, 1995,; Cohen 2006). Insecticide-induced reproductive stimulation varies among rice varieties, insecticides, and application rates (Yin et al, 2008). Sub-lethal doses of methyl parathion and decamethrin applied topically to 5th instar BPH nymphs increases the reproductive rates of adults developing from the treated nymphs (Chelliah et al, 1980). Sub-lethal application of deltamethrin results in significantly more brachypterous BPH adults than sub-lethal doses of imidacloprid or triazophos. Sub-lethal doses of some insecticides increase the fecundity of BPH females by stimulating changes in rice plant nutrients (Wu et al, 2001, 2003; Yin et al, 2008). The highest reproductive rate of BPH occurred on plants treated with triazophos. BPH adults developing from nymphs that fed on insecticide-treated plants had significantly more crude fat than those that fed on untreated plants. Reproductive stimulation attributed to insecticide treatment was more pronounced in BPH susceptible cultivars.

Philippine rice farmers apply insecticides below the recommended rates (Litsinger, 2008) while Bangladesh rice farmers usually apply granular insecticides at about half the recommended rates and foliar sprays at about 88% of the recommended rates (Hasan et al, 2008). Applications of sub-lethal rates by farmers could enhance BPH's reproductive and migratory capacity, and theoretically increase the threat of outbreaks even if the insecticides did not harm natural enemies.

Genetic resistance to the organochlorine compound BHC appeared in BPH populations in Japan in 1967, about 15 years after the insecticide was first used on that country's rice (Miyata, 1989). Researchers detected resistance to malathion and diazinon in BPH populations at IRRI's experimental farm in the Philippines in the late 1960s and 1970s (Heinrichs, 1979, 1994) and resistance to organophosphorus and carbamate insecticides appeared in Taiwan in the 1970s (Miyata, 1989). By the early 1990s, numerous Asian countries had reported BPH resistance to organochlorine, organophosphorus, carbamate and pyrethroid insecticides (Nagata et al, 1979; Kilin et al, 1981; Miyata, 1989; Hirai, 1993; Heinrichs, 1994). In 2008, laboratory assays confirmed imidacloprid resistance in BPH populations in China, India, Japan, Indonesia, Malaysia, Taiwan, Thailand and Vietnam (Gorman et al, 2008; Matsumura et al, 2009).

There are indications that continuous heavy use of the insecticides will exacerbate the problem of genetic resistance in BPH populations in China and other countries (Heong et al, 2011) including Japan where BPH emigrate annually from China. The imidacloprid-resistant BPH migrants may quickly spread from China to other countries (Wang et al, 2008b). Review of the extensive literature on the subject suggests that insecticides are the single most tangible human-controlled input responsible for BPH outbreaks. The two international conferences on rice planthoppers in 1979 and 2008 concluded that the heavy use of insecticides was the primary driving force behind BPH outbreaks (Bottrell and Schoenly, 2012).

III.5. Ecosystem functions

An ecosystem continually cycles energy, nutrients and materials within itself and eventually with other systems. The functions of an ecosystem pertain to the exchanges and interactions between the living and non-living components. Mankind benefits from a multitude of resources and processes that are supplied by natural ecosystems. Ecosystem services (discussed in section III.3.3) are the processes by which the environment produces resources that humans often take for granted such as crops, clean water, timber, a habitat for fisheries, pollination of native and agricultural plants, and others.

At this point, the need to understand how the rice system functions and the services it provide particularly to invertebrates, and how to exploit or utilize the ecosystem services for the control of rice pests is now very clear.

Altieri and Nicholls (1999) identified the components, functions and enhancement strategies for biodiversity in agroecosystems (Figure 5) which are also relevant to rice production systems. They listed non-crop vegetation, herbivores, predators and parasites, pollinators, earthworms, soil microfauna and mesofauna as the components of an agroecosystem. Interestingly, almost all except non-crop vegetation and soil microfauna include invertebrates which reemphasizes the importance of invertebrates in agroecosystems. These invertebrate components perform many functions which are directly important to rice production and many others which lead to nutrient cycling, soil improvement for crop production, and pest and disease regulation (Figure 4). However, for the purpose of this review; the main interest is the regulatory function performed by invertebrates for the biological control of invertebrate pests.

After thousands of years of rice cultivation, a relatively stable association has evolved between rice insect pests and their natural enemies (Heinrichs, 2011). When this stability is upset, e.g. destruction of predators by insecticides; insect outbreaks are precipitated. In the former traditional rice production systems, the ecosystem regulatory services were sufficient to maintain stable rice production. The RGR technologies changed all this by introducing serious modifications in crop management (large scale irrigation, crop intensification, reduction in genetic diversity, misuse of inorganic inputs) which weakened the pest regulatory service and led to the creation of secondary pests and widespread outbreaks.

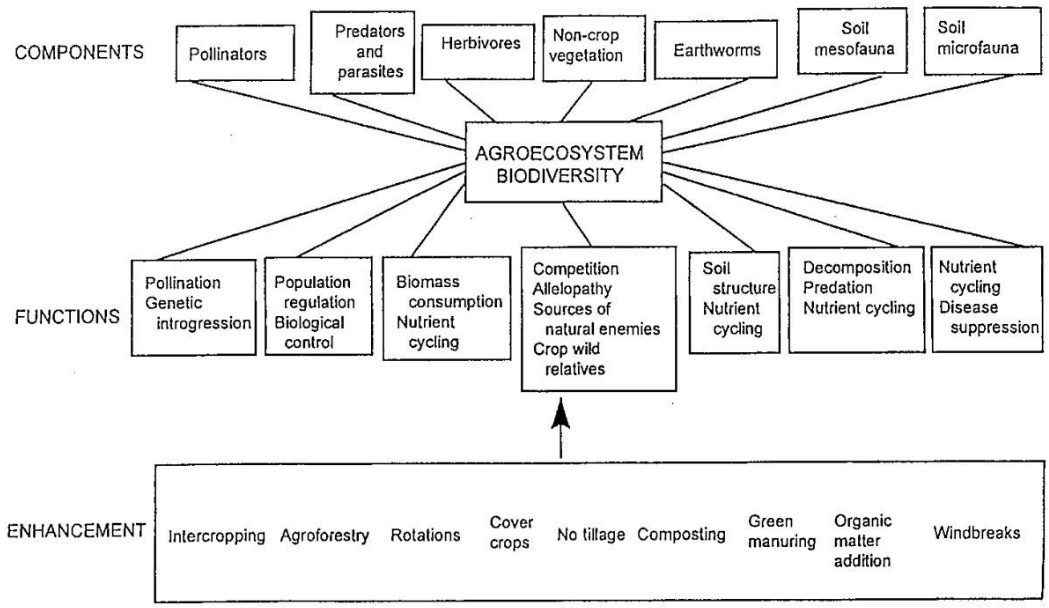

Figure 5. Components, functions and enhancement strategies for biodiversity in agroecosystems (After Altieri and Nicholls, 1999; Taken from New, 2005)

However, these conditions can be reversed to make local environments which are either less favorable for pests or more favorable for natural enemies. Such an objective is achieved by reestablishing strong linkages between pests and natural enemies through 'ecological engineering' (see section III.3.3 above).

Sections III.2 and III.3 above discussed how the biological control of rice pests functions in tropical irrigated rice. The main pillars of this biological control system are the rich composition and diversity of natural enemies, and the presence of plankton feeders and detritivores at high densities at the start of the season which supports and boosts the generalist invertebrate predators, giving them a head start in the early growth stages of the rice plant.

However, precise knowledge about how biological control performs under the aerobic rice or upland rice conditions; and rice cropping under wet and dry condition are lacking. Such knowledge is important especially because shortage of irrigation water and global warming are likely to increase aerobic rice cropping and rice cropping under wet and dry conditions. Rice cropping under alternate wet and dry conditions is already practiced by farmers in many areas, e.g. the Zanghe Irrigation System in the Yangtze River Basin of China (Bouman et al, 2007).

In the 1960s and 1970s, IRRI routinely applied eight sprays per year to rice grown in its research farm at Los Baños, Philippines (Heong et al, 2007). An average of 6.86 kg a.i. of pesticides was applied per ha per year, 55% of which were insecticides. Of the 13 insecticides used, 11 were classified as WHO category II hazardous compounds. In the early 1990s, IRRI implemented an IPM policy on the farm where insecticide was administered only when pest densities exceeded a certain threshold. As a result, pesticide use declined to about 1.0 kg a.i. per ha per year, an 85% reduction (Heong et al, 2007). At the same time, arthropod composition and structure significantly changed, i.e. herbivore abundance declined from 46.2% to 11.6% while natural enemies increased from 45.6% to 62.3%, and detritivores from 8.1% to 26.1% (Table 13). This fascinating case study clearly demonstrated that restoration and improvement in pest regulation ecosystem services are possible even from intensive pesticide application dependent systems if pesticide misuse is halted.

Table 13. Effects of the adoption of IPM strategies on arthropod diversity and abundance at IRRI research farm in Los Baños, Philippines

Guild	Diversity Parameters	Under High Pesticide Use (1989)	More than a Decade afterIPM Adoption (2005)
Herbivores	Abundance (%)	46.2	11.6
	Species richness, S or E_{sn} (rarefaction)	13.6	36
Predators	Abundance (%)	40.0	58
	Species richness, S or E_{sn} (rarefaction)	37.6	65.0
Parasitoids	Abundance (%)	5.6	4.3
	Species richness, S or E_{sn} (rarefaction)	17.1	38.0
Detrivores	Abundance (%)	8.1	26.1
	Species richness, S or E_{sn} (rarefaction)	5.6	30.0

Source: Adapted from Heong et al (2007)

III.6. Contributions to livelihoods

So far, no studies have quantified the contributions made by invertebrate diversity to the livelihoods of rice farmers since ecosystem services have indirect effects on rice yields. There is a broad statement signifying their importance which says ‘production of rice and other field crops in the absence of ecosystem regulating services being provided by the invertebrate natural enemies would have been extremely difficult indeed’. However, there are some estimates of benefits in terms of national and individual farmer’s savings.

It was calculated that the cost savings from research leading to increased insect pest management efficiency on rice in South and Southeast Asia was $973 million in insecticide costs saved by the year 2000 (Heinrichs, 2011). The adoption of an IPM policy and the banning of 57 pesticides in rice in the mid 1980s saved the Indonesian government more than $100 million per year from pesticide imports. A recent study of the three ‘reduction programs’ (reduced seed, fertilizer and pesticides) being implemented in Vietnam estimated a saving of $57 per ha which was mostly from the reduction in pesticide use. This is a significant saving for poor subsistence farmers.

IV. Regional analysis of the most relevant invertebrate species in rice ecosystems

There is insufficient data to conduct a regional analysis of the status and trends of invertebrates in rice production systems. However, one study on irrigated rice conducted in Indonesia by Settle et al (1996) gives a complete picture of the invertebrate food web functions and services. This may be applicable to Asian rainfed lowland rice where water stays in the field for extended periods. No comparable data exists for other rice regions and other rice environments.

As mentioned earlier, straight-forward comparisons between traditional rice systems and high input-based rice production systems are not possible for several reasons. In early studies, plankton feeders and all minute invertebrates; and probably, other parts of the aquatic communities were ignored largely because of inefficient sampling equipment. Nevertheless, despite these limitations; a very important regional analysis matrix based on various assumptions and experiences is shown in Table 14. The said table clearly shows the limited knowledge about the subject.

Table 14. Regional analysis of the status and trends in invertebrates of rice production systems

Functional Group	**Rice Production Environment** (planted area)	**Regions**	**Status of Resources** Also shows notes on pests and herbivores	**Remarks (including on cultivation practices)**
Soil Ecosystem Engineers Examples: Ants, termites, crustaceans, molluscs and earthworms. Examples of some species: *Lasius flavus*, *Pogonomyrmex* spp., *Formica* s. str., *Odontotermes* n. *pauperans*, *Macrotermes bellicosus*, *Dendrobaena* spp., *Lumbricus* spp., *Eiseniella tetraedra*, *Heliodrilus oculatus*, *Allolobophora chlorotica*, *Apporectodea* spp., *Murchieona muldali*, *Octolasin* spp.	Irrigated systems with season-long flooded condition (Worldwide 89.2 million ha)*	Asia including Oceania (82.6 million ha)	Unknown; a rich and diverse community of ecosystem engineers may be present but in some areas, is probably partly affected to some extent by insecticides and herbicides applications.	Need to study and stop misuse and overuse of insecticides and herbicides
		Africa (1.9 million ha)	Unknown; probably similar to Asia	Need to study
		South America and the Caribbean (2.6 million ha)	Unknown; probably similar to Asia	Need to study
		North America and Europe (2.2 million ha)	Unknown	Need to study
	Rainfed lowland system including deepwater and tidal wetlands with aerobic and anaerobic conditions (Worldwide 50.7 million ha)	Asia including Oceania (46.2 million ha)	Unknown, probably somewhat similar to irrigated systems in Asia	Need to study
		Africa (4.5 million ha)	Unknown; probably somewhat similar to Asia	Need to study
		South America and the Caribbean	No rainfed lowland rice	
		North America and Europe	No rainfed lowland rice	
	Upland rice systems (Worldwide 14.0 million ha)	Asia including Oceania (8.0 million ha)	Unknown; it is important to know status of soil ecosystem engineers in upland systems	Need to study
		Africa (2.8 million ha)	Unknown; interesting to know? (31% of rice area is upland)	Need to study
		South America and the Caribbean (3.3 million ha)	Unknown; it is important to know (56% rice area is upland)	Need to study
		North America and Europe	No upland rice	
Biological Control (BC) Agents Important Examples: **Predators:** *Cyrtorhinus*	Irrigated systems (Worldwide 89.2 million ha)*	Asia including Oceania (82.6 million ha)	Diverse and rich communities of natural enemies (NE) are active, generally capable in keeping pests populations under control	Need to stop insecticide misuse; ecological engineering (EE) can improve BC

lividipennis, *Lycosa pseudoannulata*, *Microvelia douglasi atrolineata*, *Mesovelia vittigera*, *Ophionea nigrofasciata*, *Metioche vittaticollis*, *Anaxipha longipennis* **Parasitoids:** *Tetrastichus schoenobii*, *Trichogramma japonicum*, *Telenomus rowani*, *Angrus* spp., *Copidosomopsis nacoleiae*, *Cotesia flavipes*, *Xanthopimpla stemmator*, *Goniozus* nr. *Trangulifer*, *Macrocentrus philippinensis*				further
		Africa (1.9 million ha)	Unknown, probably somewhat similar to Asia	EE can improve BC further
		South America and the Caribbean (2.6 million ha)	Unknown, probably somewhat similar to Asia	EE can improve BC further
		North America and Europe (2.2 million ha)	Unknown, may be lower NE richness and diversity than Asia because of limited non-rice habitats in the ecosystems of large farms	EE can improve BC further
	Rainfed lowland system including deepwater and tidal wetlands with aerobic and anaerobic conditions (Worldwide 50.7 million ha)	Asia (including Oceania (46.2 million ha)	Unknown, but probably somewhat similar to irrigated system	Need to study. EE can improve BC further
		Africa (4.5 million ha)	Unknown, but probably somewhat similar to Asia	Need to study. EE can improve BC further
		South America and the Caribbean	No rainfed lowland rice	
		North America and Europe	No rainfed lowland rice	
	Upland rice systems (Worldwide 14.0 million ha)	Asia including Oceania (8.0 million ha)	Unknown; it is important to know?	Need to study EE can improve BC further
		Africa (2.8 million ha)	Unknown; it is important to know (31% of rice area is upland)	Need to study EE can improve BC further
		South America and the Caribbean (3.3 million ha)	Unknown; it is important to know (56% rice area is upland)	Need to study; EE can improve BC further
		North America and Europe	No upland rice	
Herbivores (insect pests and vectors) Important examples: **Asia** *Nilaparvata lugens*, *Sogatella furcifera*, *Scirpophaga incertulac*, *Chilo suppressalis*, *Cnaphalocrocis medinalis*, *Nephotettix* spp.,	Irrigated systems with season-long flooded condition (Worldwide 89.2 million ha)*	Asia including Oceania (82.6 million ha)	A very diverse complex of herbivores: out of 322 species of herbivores 20-30 species of pests and several plant and human disease vectors that develop in rice fields. RGR technologies changed the status of some pests, and misuse of insecticides created secondary pests (planthoppers); plant resistance break down	Need to stop insecticide misuse and overuse of nitrogen fertilizer; adopt wet and dry system of irrigation; EE can contribute to stability

Leptocorisa spp., *Orseolia oryzae*, *Dicladispa armigera*, *Pomacea canaliculata* **Africa** *Diopsis* spp., *Orseoliaoryzivora*, *Pseudaletia unipuncta*, *Maliarphaseparatella*, *Sesamia aclamistis*, *Micritermes* **USA** *Lissorhoptrus oryzophilus*, *Triops Longicaudatus*, *Diatraea saccharalis*, *Chilo plejadellus*, *Pseudaleta unipuncta*, *Oebalus pugnax*, *Tagosodes orizicoles* **South & Central Amercia and the Caribbean** *Diatraea saccharalis*, *Tagosodes orizicoles*, *Rupola albinella*, *Elasmopalpus lignosellus*, *Spodoptera frugiperda*			and resistance to insecticides, causing widespread outbreaks.	
		Africa (1.9 million ha)	A diverse complex is present, invertebrate pest pressure seems lower than Asia; out of 110 herbivore species 10-15 considered as pests. Stalk-eyed borer most prevalent in irrigated areas; other major pests include gall midge and stem borer; BPH and GLH are present.	Should not misuse insecticide and should avoid overuse of nitrogen fertilizer.
		South America and the Caribbean (2.6 million ha)	A diverse complex is present, out of 126 invertebrate herbivores, may be 10-15 are major pests. Asian rice planthoppers are absent but rice delphacid *Tagosodes orizicoles* is present which transmits Hoja Blanca virus.	Should not misuse insecticide and should avoid overuse of nitrogen fertilizer.
		North America and Europe (2.2 million ha)	Of 60 species of invertebrate herbivores about 10 are pests. Important pests are water weevil, stink bug, tadpole shrimp, crayfish, seedling midge, leaf miner, sugarcane borer, and rice stalk borer and army worms.	Restrain from misuse of insecticides and overuse of nitrogen fertilizer.
	Rainfed lowland system including deepwater and tidal wetlands with aerobic and anaerobic conditions (Worldwide 50.7 million ha)	Asia including Oceania (46.2 million ha)	Probably similar to Asian irrigated rice environment	Same as Asian irrigated rice
		Africa (4.5 million ha)	Probably similar to African irrigated rice	Same as African irrigated rice
		South America and the Caribbean	No rainfed lowland rice	
		North America and Europe	No rainfed lowland rice	
	Upland rice systems (Worldwide 14.0 million ha)	Asia including Oceania (8.0 million ha)	Unknown: generally, soil pests such as termites, ants, white grubs, and mole crickets are important in addition to RLF, stem borer, leaf and planthoppers.	Need to be studied
		Africa (2.8 million ha;	Unknown, may be similar to Asian upland	Need to be studied

		31%)	rice above (31% of rice area is upland)	
		South America and the Caribbean (3.3 million ha, 56%)	May be similar to African upland rice above (56% rice area is upland)	Need to be studied
		North America and Europe	No upland rice	

* rice area based on 2010 estimated data (IRRI GIS)
BC – biological control; BPH – brown planthopper; EE – ecological engineering;
GLH – green leafhopper; RLF – rice leaffolder

IV.1. Soil ecosystem engineers

Organisms known as ecosystem engineers play a major role in creating, modifying, maintaining and destroying the habitats that other species depend upon. By controlling the flow of energy and materials, they can profoundly affect the way ecosystems function. Ecosystem engineers come in myriad forms as plants, animals and tiny microorganisms. The discussion here will be restricted to the dominant invertebrate ecosystem engineers, namely: nematodes (eelworms), annelids (earthworms), arthropods (ants, termites) and mollusks. These forms affect soil properties and availability of resources for other organisms including microorganisms and plants. However, the link between their impacts on the soil and the resulting modification of natural selection pressure on the engineers as well as on other organisms, has received little attention (Jouquet et al, 2006). Similarly, there has been no breakdown of ecosystem engineers by rice cultural type.

IV.2. Biological control agents

Predators, parasitoids, parasites and pathogens are biological control agents of rice invertebrate pests. The large and diverse complex of invertebrate natural enemies present in Asian rice was described in section III.3. However, it is difficult to separate the diversity and abundance of natural enemies in the different rice environments (irrigated, lowland rainfed and uplands) from the available literature. Moreover, little is known about the diversity and abundance of biological control agents in the different rice environments of other regions. A careful review of all available literature may yield useful information.

IV.3. Herbivores

A large complex of invertebrate herbivores is active in rice production systems. However, the data on their diversity and abundance are not grouped under different rice production environments except upland rice. A detailed review of current literature is needed to provide better rice environment-wise information. To date; a total 527 species of invertebrates have been recorded as feeding on the rice plant (Table 15), 97% of which are insects and the rest are mainly crabs, snail, nematodes and mites.

Diversity in the Asian region is more than double that of Africa, and of South and Central America, and the Caribbean; and nine-fold greater than USA plus Europe (Table 15). The reason for Asia's high diversity is probably due to the long association between herbivores and rice, the extensive rice areas in a variety of climates and floral regions, and the greater number of rice cultural types grown in Asia. It may also be influenced by the more intensive studies conducted in Asia than in the other regions.

Table 15. Diversity of invertebrates feeding on rice plants, by region

Rice regions	**Number of Species**	**Percent***
Asia and Oceania	322	61.1
Africa	110	20.9
South & Central America and the Caribbean	126	23.9
USA and Europe	37	7.0
Total species	527	

*Percentages add up to more than 100 because some species are present in more than one rice region.

Source: Catling 1980; Reissig et al, 1986; Dale, 1994; Pathak and Khan, 1994; Litsinger et al, 1987; Godfrey, 2003; Heinrichs, 2011; and various WARDA Annual Report

V. Areas under risk of critical loss of invertebrate diversity and related ecosystem services

Based on earlier discussion of data and information, it is very clear that the abused use of insecticides coupled with excessive N fertilizer application can precipitate serious outbreaks of planthoppers, and that this phenomenon is associated with often irrigated HYV rice production systems. This shows that irrigated rice systems are potentially high risk areas of invertebrate and ecosystems services loss. Figure 6 shows the world distribution of irrigated rice areas. There is the need now to incorporate information on insecticide application and fertilizer use to further refine the assessment of future high risk areas.

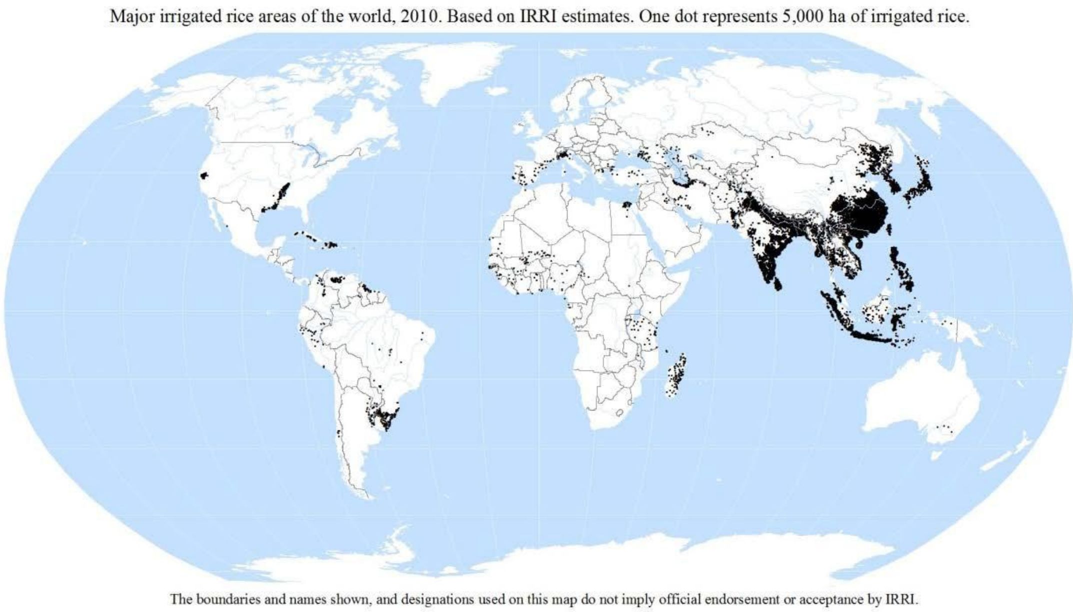

Figure 6. Distribution of irrigated rice areas in the world; (Source: GIS, SSD, IRRI)

The assessment will consider the insect pests first. Planthoppers which are probably the major insect pest group that threatens Asian rice, are present throughout the sub-tropical and tropical Asian and Pacific rice areas, and they have reached the temperate regions of Asia through annual migration. The Asian rice planthoppers are also present in Africa (Kaung et al, 1984) where about 20% of the rice areas are irrigated and 42% are under rainfed lowlands (Table 3). In Asia, 31% of the rice areas are rainfed lowlands consisting of gradients of hydrological conditions close to upland conditions at one end of the spectrum to deepwater conditions at the other end. In between these two extremes, high input-based rice production is possible. Central and South America, the USA and the Caribbean do not have the Asian planthoppers. However, other delphacids are present but the 'rice delphacid' Tagosodes orizicoles is considered the most important because it causes hopperburn and serves as the major vector of Hoja Blanca virus. This species appears less devastating than the Asian rice planthoppers.

Rice in Europe and Australia is grown under irrigation but planthoppers are not known there.

Table 4 shows that fertilizer use in most of the major rice growing countries is increasing at an alarming rate. The increases from 2001 to 2007 are phenomenal, i.e. 68% in Thailand, 52% in Indonesia, 40% in China, 38% in Brazil and 33% in India. The average rate of nitrogen used per hectare per crop in 2007 varied among countries, with the lowest of 25 kg/ha in Thailand and highest of 229 kg/ha in the USA. In general, most countries applied about 100 kg N per ha which is enough to get 6 t/ha rice yield in the dry season (Rice Knowledge Bank).

The average application rate of 100 kg N/ha implies that about half of the rice fields receive more than that rate. Therefore, the cut off rate for the identification of a high risk area can be 100 kg N/ha. Based on this N rate; China, Malaysia, Iran, Vietnam, Pakistan, Bangladesh, and India can be considered as high risk countries in Asia followed closely by Indonesia (Table 4). Among these high risk countries, China uses almost double the cut-off rate (193 kg N/ha) followed by Malaysia (136 kg N/ha) and Iran (119 kg N/ha), and the others are close to the threshold. Since BPH is also present in Africa, Egypt with 169 kg N/ha can also be considered as a high risk area. Although N use is high in the USA (229 kg N/ha), Turkey (141 kg N/ha) and Argentina (106 kg N/ha); these countries are not considered as high risk due to the absence of Asian planthoppers. However, the rice delphacid *T. orizicoles* can cause problems in Latin America and the USA. Europe has also been excluded from the high risk list because of the absence of Asian planthoppers.

Insecticide use is the most important factor in understanding the loss of biodiversity in rice and in accounting for rice planthopper outbreaks. The available knowledge of insecticide use in rice is mostly superficial because historical data are not readily available by country. National officials are most reluctant to provide data on insecticide use.

In the past, Japan and South Korea were the two countries applying the highest amounts of insecticide on rice in Asia. Japan was intensively using insecticides even before the start of RGR. Before 1968, South Korea was making two applications per season but in 1972, the government officially recommended four applications on *japonica* rice and five on the Tong-il (HYV) variety (Catling, 1973). In 1973, Korean farmers were making an average of eight applications per season because of the susceptibility of Tong-il variety to stem borers, BPH, and leaf and sheath blight. Recent data of insecticide use in Japan and South Korea are not available.

In the early 1990s, the IRRI- led Farmer Participatory Research program conducted surveys in nine countries in Southeast Asia which estimated the frequency of insecticide applications (Escalada and Heong, 1997). Two decades later in 2011, the FAO-IRRI Pesticide Supply Chain Survey also estimated the number of sprays applied to rice by farmers (Table 16). There was a significant escalation in insecticide use during the two decades, and the current situation seems worse than it was in the early days of the green revolution. Applications tremendously increased in Laos and Cambodia which joined the RGR late, in the 1990s. Vietnam was the only country where insecticide applications decreased (from 3.9 to 3.2). This may have been due to the implementation of FAO-led IPM program, IRRI-led extensive farmer participatory research, and the ‘seed, fertilizer and insecticide reduction program’ followed by a mass media (radio and TV) campaign, and the government’s recent efforts to curb insecticide misuse. As a result, Vietnam did not experience severe planthopper outbreaks after 2008. On the other hand, China and Thailand continued to suffer from severe planthopper outbreaks. Since fertilizer use in Thailand is low (Table 4), it appears that these planthopper outbreaks are almost entirely due to the misuse of insecticides.

Based on the insecticide use pattern and the history of planthopper outbreaks, it appears that three or more applications of insecticides per season can sufficiently reduce invertebrate diversity and pest regulatory services in order to trigger planthopper outbreaks. Considering the past records, it can be assumed that the present insecticide application frequency in Japan and South Korea is more than three times per season.

Table 16. Frequency of insecticide application to rice in selected Asian countries in 1992 and 2011

Country	1992*	2011			
	Application Frequency (no./season)	Application Frequency (no./season)	Increase over 1992 (%)	Timing of First Application (DACE)**	Reference
Bangladesh	-	0.8 -1.4***	-	-	Hasan et al, 2008
India	-	8.0$	-		Shetty, 2004
China	3.6	8.0$$	12	-	FAO-IRRI Pesticide Supply Chain Survey, 2011 (unpublished)
Cambodia	0.7	5.1	52	19	
Indonesia	2.7	5.8	11	18	
Laos	0.3	5.2	163	24	
Malaysia	1.9	5.2	17	24	
Myanmar	-	1.2	-	29	
Philippines	3.3	2.5$$$	-	-	
Sri Lanka	1.4	-	-	-	
Thailand	2.3	4.3	8	2555	
Vietnam	3.9	3.2	-	32	

* Source: Heong and Escalada, 1997;**DACE = days after crop establishment; ***0.8 times in the wet season and 1.4 times in the dry season, from survey in 2001; $ Study in India carried out in late 1990s; $$Study in one season in 2009; $$$Survey conducted in Nueva Ecija Province only.

The two indicators which are associated with the loss of invertebrate diversity and pest regulatory services, and which trigger planthopper outbreaks can now be considered. These are the average nitrogen fertilizer use of more than100 kg N/ha, and an insecticide application frequency of three or more per season. These indicators are listed by country in Table 17 and compared with the BPH outbreaks in 2009 in an attempt to determine future high risk areas.

The countries scoring in all three criteria are classified as *very high risk areas* for loss of invertebrate biodiversity and ecosystem's pest regulatory services, and are more likely to lead in planthopper outbreaks. Irrespective of N application rate or pest outbreak record in 2009, countries applying insecticides three or more times per season are regarded as *high risk areas*. Other countries using higher rates of N or experiencing planthopper outbreaks in 2009 or both, are considered as *moderate risk areas*.

According to these definitions, the countries can be classified as follows:

- *Very high risk areas*: China, India, Malaysia, South Korea
- *High risk areas*: Cambodia, Indonesia, Japan, Laos, Thailand
- *Moderate risk areas: Bangladesh, Iran, Pakistan, Philippines, Vietnam*

Table 17. Indicators of invertebrate biodiversity and pest regulatory service loss leading to rice planthopper outbreak potential (√) in selected Asian countries

Country	Invertebrate Biodiversity and Pest Regulatory Service Loss and Planthopper Outbreak Criteria		
	Nitrogen Fertilizer Use	**Frequency of Insecticide Application**	**Outbreak in 2009**
Bangladesh	√	-	√
Cambodia		√	
China	√	√	√
India	√	√	√
Indonesia		√	
Iran	√	-	-
Japan	(√)	(√)**	-
Republic of Korea	(√)	(√)	√
Laos		√	
Malaysia	√	√	√
Pakistan	√	-	
Philippines			√
Thailand		√	
Vietnam	√	√	

* Data not available, ** Current data not available; (√) Judgment made from past record

The current situation of insecticide use in Bangladesh, Iran and Pakistan is not known, and it is uncertain for the Philippines. If the application frequency is three times or more, then Bangladesh would qualify for the very high risk category, and Iran and Pakistan would enter the high risk category. If Vietnam continues to curb insecticide misuse, then it may be dropped from the moderate risk list. Available data for the Philippines is based on one survey in the province of Nueva Ecija where the average frequency of insecticide application exceeded three times per season. If this is representative for the country, then the Philippines will enter the high risk category. Although only 14 out of the world's 114 rice growing countries were considered in this risk assessment, these countries comprise 81% of the rice area and produce 82% of the world's rice.

VI. Current constraints and opportunities

VI.1. Constraints

VI.1.1. Insecticide abused use

The misuse and overuse of agrochemicals are a major constraint to invertebrate diversity and abundance, and can always cause a breakdown of ecosystem services for pest management in rice production systems. Among the agrochemicals, insecticides are the main culprit. Insecticides indiscriminately kill invertebrates both in the crop canopy and paddy water. Natural enemies escaping contact with insecticide sprays will later collect insecticide deposit while searching for their prey (predators) or hosts (parasitoids) and perish. As discussed earlier, the problem of rice planthoppers and leafhoppers is created by the misuse of insecticides (Heong, 2009).

Despite several massive IPM training schemes for farmers for more than two decades, insecticide misuse (and overuse of nitrogen fertilizer) is still increasing. In most Asian countries, pesticides are sold using fast moving customer goods (FMCGs) marketing strategies. Like the marketing of soap, washing powder, cosmetics, soft drinks, toothpaste and shampoo; the pesticide market is also driven by aggressive advertising which embraces emotional appeals to which Asian rice farmers succumb. The developed world has regulations to curb and limit the misuse of pesticides but these are absent in most Asian countries. Inexperienced and untrained application personnel as well as unsafe and often unsuitable application equipment cause additional problems such as pesticide poisoning, environmental pollution, and ineffectiveness.

VI.1.2. Herbicide misuse

Traditionally, rice weeds are mainly controlled manually with the help of simple hand tools, and by water management. Herbicide use in rice first became popular in Japan and Korea. From the 1990s, it started to spread more widely to the rest of Asia particularly Malaysia and Thailand due to the associated spread of the less labor-intensive practice of direct seeded rice. Herbicide applications are especially harmful to the invertebrates of rice ecosystems when farmers spray the non-rice habitats to kill the weeds and the vegetation that harbor the associated invertebrates including natural enemies.

VI.1.3. Nitrogen fertilizer overuse

Farmers in many major rice producing countries are using nitrogen fertilizer in excessive rates which are still increasing (Table 4). The over use of nitrogen not only contributes to outbreaks of planthoppers and other pests but it also makes rice plants susceptible to several diseases.

VI.1.4. Hybrid rice and overuse of chemical inputs

It is claimed that hybrid rice increases yields by 15 – 20% over inbred varieties. Hybrid rice is mostly promoted by privately-owned seed firms which are often supported by the government in many countries. These firms promise bumper production to farmers by using hybrid varieties rather than their current varieties (which are often not true). Hybrid rice farmers use nitrogen and insecticides at much higher rates than those used for the former inbred high yielding varieties. Currently, about 60% of Chinese rice lands is planted to hybrid rice where farmers are using nitrogen and insecticides at very high rates (IRRI, 2006). The time has definitely come to critically examine the costs and benefits of hybrid rice production to farmers, consumers, and environment.

VI.2. Opportunities

VI.2.1. Attention to food safety

The issue of food safety has attracted remarkable attention in the developed world but it has drawn very little concern in developing countries where rice is mostly grown. In recent years; the safety of using preservatives on fruits, vegetables and fishes was a common and popular concern in some countries. However, pesticide residues in rice has not yet been an issue of concern in the rice growing countries, and monitoring of pesticide residues in rice has drawn very little research attention. Research and campaign for food (rice) safety will have negative influence on the abused use of pesticides in rice. Rice producing countries should adapt rice pest control resolutions like those adopted recently in the of the Ramsar International Wetlands Conservation (COP-XI) which propose that the use of high pesticide levels is inappropriate for conservation in rice paddies (www.ramsar.org/pef/copXI).

VI.2.2. Reduction of insecticide use

Irrigated rice ecosystems are blessed by a diverse and rich complex of invertebrates. The ecosystem regulatory service in the form of biological control can generally maintain rice production without significant pest damage or yield loss. In order to realize this opportunity, farmers need to avoid the abused use of insecticides and herbicides, and steer away from the excessive use of nitrogen fertilizer. Curbing the misuse of insecticides does not seem easy because of the vested interests of pesticide companies, distributors and the collusion of some government officials who work to encourage pesticide misuse. Farmers have also developed an insecticide use habit which is not based on rational economics because of their perception that insecticide applications will always save their crops from significant losses. However, stopping the misuse of insecticides is not an impossible task but it needs political will and dedication of government officials in protecting farmers' and consumers' interests. Currently, Vietnam seems to be taking the right path and can serve as the model to be followed by other countries.

VI.2.3. Judicious use of herbicides

Traditional weed management practices in Asian rice are far more eco-friendly than herbicide use. However, the labor shortage and the hike in labor costs are encouraging farmers to use herbicides. As mentioned earlier, herbicides are most damaging to the invertebrates of rice ecosystems when applied to non-rice habitats including rice bunds. The motivation for the judicious use of herbicides as well as insecticides should go hand in hand.

VI.2.4. Ecological engineering

Ecological engineering as a new approach for maximizing natural biological control has been experimented with and successfully demonstrated during 1970s and 1980s in Zhejiang, Jiangshu and Anhui provinces of China. Recently; China, Vietnam and Thailand are collaborating with IRRI to introduce the ecological engineering approach in rice, and the results are encouraging. Adoption of ecological engineering enhances natural biological control; and hopefully, the R and D for insect pest management in rice in most rice growing countries will follow this new direction.

VI.2.5. Real-time nitrogen management

The leaf color chart (LCC) is a simple, inexpensive tool enabling farmers to apply nitrogen fertilizer according to the need of the crop. Research has shown that adoption of LCC reduces nitrogen fertilizer use in rice so that the crop suffers less insect pest and disease problems resulting in reduced pesticide use. Studies in West Bengal, India indicated that the adoption of real-time nitrogen management based on LCC not only reduced nitrogen and insecticide use but also made rice production more profitable (Islam et al, 2007). This is an IPM component technology that needs to be taken seriously.

VI.2.6. Rice-fish culture

In the past, free-living fish was an important resource in the lowlands of Asia. Fishes feed on insects falling into, dispersing through, and living in the water. Fish also eats mosquito larvae and other aquatic insects, reduces the density of aquatic weeds, and increases soil fertility. Unfortunately; rice fish culture has declined due to the widespread use of semi-dwarf modern rices, spread of irrigated rice cropping in the dry season, and greater insecticide use. However, in some regions; it is regaining popularity as the demand for fish increases. The adoption of rice-fish culture discourages insecticide use and enhances biological control.

VII. Looking forward: preparing for the future

Future demand for rice will depend on the growth, age, structure, income, and degree of urbanization of the population. Rice demand in Asia is expected to grow by about 1% a year until 2025 (Sombilla et al, 2002). In West and Central Africa, demand for rice is currently growing at 6% a year which is faster than anywhere else in the world. This growth is largely the result of urbanization and changing consumer preferences favoring rice. The main challenge facing most major rice-producing and -consuming countries is to provide sufficient affordable food for the growing and urbanizing populations, and alleviate rural and urban poverty (Bouman et al, 2007). This has to be done under increasing pressure on land, water, and labor resources which threaten the sustainability of the rice production base.

VII.1. Producing more rice with less water

Irrigated rice receives about 24-30% of the world’s total freshwater withdrawals (Bouman et al, 2007). Before the RGR in Asia, water used to be a priceless resource but not anymore. River water sharing is emerging as a major source of conflict between neighboring countries. Pumping out large volumes of underground water for irrigation has led to serious arsenic contamination in the irrigation and drinking water in Bangladesh and West Bengal, India. The looming water crisis is forcing farmers and scientists to innovate more efficient water management practices.

The Zanghe Irrigation System in the middle reaches of the Yangtze Basin in China has a command area of about 160,000 ha and mainly produces summer rice. Since the early 1970s, the amount of water released to agriculture has been steadily reduced in favor of the cities, industry, and hydropower. By the mid-1990s, the amount of water allocated to agriculture had declined to less than 30% of that received in the early 1970s. In the same period, however, rice production increased, peaking to about 650,000 metric tons in the late 1980s which was nearly twice the amount produced in the late 1960s. Although rice production has leveled off to a stable 500,000 metric tons in the last decade, more rice has been produced with less water over the past 30 years, because of the various integrated measures listed below:

- Replacing double rice cropping with more water-efficient single rice cropping
- Promoting alternate wetting-drying water-saving technology and aerobic rice (irrigation only to field capacity, no flooding)
- Introducing volumetric water pricing, and institutional reforms such as water user associations which promote efficient use of water by farmers
- Upgrading the irrigation system (for example, canal lining)
- Developing secondary storage through the creation of thousands of small- to large-size ponds and reservoirs

Research has shown that continuous flooding is not necessary to attain high rice yields; and periodic drainage of the rice field may not reduce yield but can even bolster yield (Singh et al, 1996). In China, periodic drainage not only reduced the volume of irrigation water by 40-70% with no apparent loss in yield (Guerra et al, 1998); it also reduced mosquito larvae and human malaria (Roger and Bhuiyan, 1990). In the face of the looming water crisis, such periodic wet and dry irrigation in rice is likely to become widespread. However, the impact of these changes on the invertebrate diversity and abundance, and natural biological control is unknown and can possibly be negative. Therefore, studies are required to investigate the situation.

VII.2. Pesticide hazards and resistance

Pesticide use poses many problems. It can cause health hazards; contaminate the environment; disrupt natural biological control mechanisms; and develop pest resistance to pesticides. Pesticides can be health hazards to farmers, farm workers, factory workers and people who are involved in storage and marketing. Long-term exposure to pesticides can cause eye, skin, pulmonary and neurological problems; enzyme disorder; deterioration of blood cells; cancer and even birth defects. Although all pesticides adversely affect the environment to some extent, insecticides pose the more serious threat because of their high acute and chronic toxicity, persistence in the environment, and cumulative properties. The continuous application of broad- spectrum pesticides always affects and often seriously disrupts the delicate balance of life in the agroecosystem as well as severely disturbs and destroys the natural enemies.

It is evident that natural enemies play a vital role in keeping pest populations at a tolerable level. Disruption of the action of natural enemies by pesticides usually lead to resurgence of target pests and outbreaks of secondary pests. Farmers usually respond by increasing the dosage and frequency of pesticide applications and/or shifting to more toxic materials. In the long-term, this vicious cycle leads to a pesticide treadmill which consequently creates serious problems such as environmental pollution and pesticide resistance.

Many pests, especially insects and mites, have developed tolerance or resistance to pesticides. Pests may develop multiple or cross-resistance when a whole group or family of compounds suddenly becomes no longer effective against them. Pest organisms have the genetic ability to evolve strains capable of surviving exposure to pesticide dosages to which earlier generations are susceptible. Surviving individuals of one generation, arising from mutations in the target species, then pass on the resistance characteristic to the next generation. Upon repeated exposure to the pesticide, genetically resistant individuals then constitute an increasingly larger part of the pest population. Genetic resistance commonly results from the biochemical capacity of a pest to convert a pesticide into non- toxic compounds.

Chemical control continues to be the main strategy for controlling rice pests with occasionally disastrous results. For example, the second wave of planthopper outbreaks in Asia was clearly associated with the misuse of insecticides and the development of resistance. In China, farmers normally apply insecticides four to five times per season but they increase the frequency to as many as 10 applications during planthopper outbreaks. Thus, in recent years; BPH and WBPH have become serious problems.

According to the studies at the Nanjing Agricultural University (pers. com. Liu, Zewen; China); abused use of insecticides in China is causing rapid development of resistance. BPH has acquired a hundred-fold resistance to imidacloprid and fipronil (Figure 7) and these two materials have been removed from the market. The resistance apparently develops in two stages known as the double 'S' curve. During the first period, biochemical factors such as the high expression of detoxification enzyme genes, are the main mechanisms. However, target insensitivity (target site mutation) is the main mechanism during the second period. The researchers believe that methods to combat the development of such resistance are only efficient when resistance levels are still in the first increase stage (Figure 8) which is associated with biochemical mechanisms.

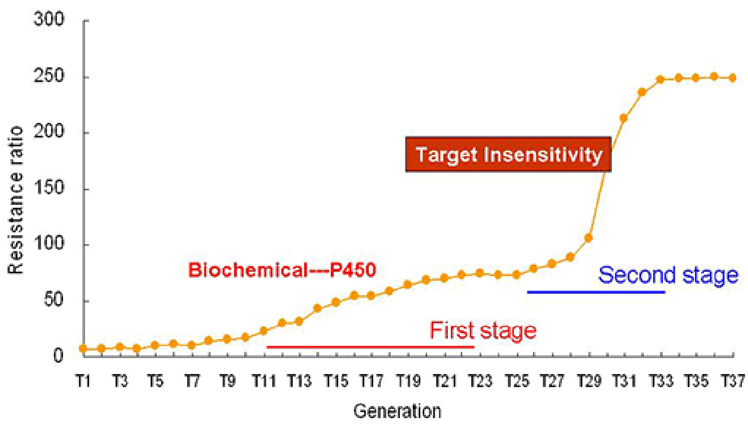

Figure 7. Development of resistance to imidacloprid and fipronil insecticides by BPH populations in China (After Prof. Z. Liu, Nanjing Agric. Univ., China)

VII.3. Cropping systems and cultural practices to improve biological control

Non-rice crops in the rice environment enhance biological control of rice pests by providing shelter and supplementary and/or alternate food for natural enemies. The varied flora in and around rice fields creates a favorable environment for many invertebrates. Crop rotation and crop mosaics in the rice environment increases biodiversity which effectively checks the growth of pest populations. Multiple crops simultaneously grown or in rotation stimulate a multitude of soil organisms which not only help to control soil-borne pathogens and weeds but also improve soil structure. Non-rice crops such as cowpea, mung bean, maize, bell pepper, garlic, onion and soybean serve as important reservoirs of natural enemies (Islam and Catling, 2012). In general, mosaics of non-rice crops within large rice blocks encourage the conservation of invertebrates, including natural enemies. Cultivation of non-rice crops in rice systems especially in dry lands and fields at higher topography are common. In addition, some other crops can be grown on the bunds of the rice fields.

Any change in a crop production practice ultimately affects the yield through complex interactions between crop and environment. All crop production practices affect pest populations to some extent either positively or negatively; and a single practice such as plant spacing or time of planting may produce opposite effects on different pest species (Islam and Catling, 2012). Continuous rice cultivation may encourage pest buildups, but it also sustains and boosts the numbers of natural enemies. The use of low fertilizer rates and the draining of water from fields are both highly effective in suppressing certain insect pests (such as planthoppers) and diseases, but may also result in lower yields if done during critical plant stages.

Cultural control relies heavily on the farmers' own labor and indigenous materials, and is relatively inexpensive. It is generally free from environmental pollution and compatible with other pest management practices but is a much slower control process than the use of pesticides or resistant varieties. Some cultural practices lead to direct benefits to the farmer when carried out at the individual farm level while others require community action to be effective. An area of at least 50 ha is usually needed for community measures to be effective. Examples of single field cultural control methods, cultural control methods requiring community action, and cultural practices that disturb natural enemies are given in Table 18.

Table18. Examples of single field cultural control methods, cultural control methods requiring community action, and cultural practices that disturb natural enemies.

Single Field Cultural Control Methods	Cultural Controls Requiring Community Action	Cultural Practices Seriously Disturbing Natural Enemies
Dry tillage	Staggered tillage in the system	Puddling by hand tractor or tractor with faster speed and wider swath
Planting method	Size and placement of crop area	Burning of rice stubble and/or straw
Seedling age	Rice cropping frequency	Trimming of non-rice vegetation from rice bunds prior to tillage and puddling
Plant density	Crop rotation	Destruction of field vegetation during fallow periods
Weed control	Varying planting time	Strict synchronous rice planting over large areas
Rogueing	Synchronous planting/harvesting	
Water management	Plant maturity	
Fertilizer management	Trap cropping Stubble destruction Ratooning	

Some cultural practices seriously disturb the invertebrates and the natural enemy complex. Puddling (tillage of flooded fields) disturbs invertebrate populations sheltering on the rice fallows and rice bunds. Hence; aerobic rice, no-till rice and SRI may offer better alternatives but their impacts on invertebrates and grain yield need to be investigated. It is better to incorporate crop residues into the soil than burn them. If burning is essential, the residues should be burned in heaps rather than over the whole field.

VII.4. Varietal diversity to enhance invertebrates

Plant-feeding insects are in a constant battle with their host plants which develop natural defense mechanisms in response to attack. Thus, insects have coevolved with their host plants. Typically, a resistant variety provides effective pest protection for the first few years after release. Then, particularly when the variety becomes popular and widely grown; it begins to suffer a little damage and later gradually succumbs to increasing pest damage until it finally fails in the field. This is explained by the fact that when a variety with a new resistance gene or genes is released, there are few pest individuals with a genetic background (genotype) that enable them to survive on the resistant variety. The offsprings of these pre-adapted individuals then survive and multiply in each successive generation so that the proportion of adapted individuals steadily increases. Thus, a pest population evolves into a new genotype that is no longer affected by the original resistant genes.

Brown planthopper was managed in Southeast Asia in the 1970s and 1980s largely by the sequential release of varieties with high resistance genes, and replacing those that failed in the field with new varieties. This strategy can only work where replacement varieties with new resistance genes are available on time. The main drawback of sequential release is that new varieties are not always available in time to prevent fresh outbreaks. On the other hand, BPH adaptation to a moderately resistant variety (several genes involved in the resistance) such as IR64 was much slower than to a highly resistant variety like IR24. Therefore, unlike IR24; IR64 is still extensively grown in Central Luzon, Philippines and elsewhere for decades.

Pests also adapt more slowly to a resistant variety if there are some susceptible plants in the area. This is because the presence of susceptible plants enable some of the non-adapted insects to survive and even mate with the adapted insects (the resistant biotype), thus decreasing the population increase rate of the adapted insects. In other words, varietal (genetic) diversity by including susceptible types in an area, is beneficial because it exerts less selection pressure on the insect pest and limits the development of ‘monsters’. Varietal diversity also plays an important role in minimizing the risk against insect pest and disease outbreaks, i.e. if one variety succumbs to a pest outbreak then farmers can still get yield from the other varieties. Studies to investigate the effects of varietal diversity including hybrid rice on the diversity and abundance of rice invertebrates still need to be conducted.

VII.5. Making pest and biological control agents monitoring available to small- scale farmers

Rice farms are almosty always small in Asia, and reaching the millions of small-scale rice farmers has always been a major challenge. However, phenomenal success has recently been achieved in electronic communication so that cell phones can now be used to make the latest agricultural information available to small-scale farmers. Today, it is assumed that most farming families in Asia have access to a cell phone. At the same time, regular agricultural programs on national TV channels can supplement the information reaching small-scale farmers. However, such interventions may not replace quality ecology-literacy training which is expensive and time consuming in order to reach the vast number of rice farmers.

Research systems need to develop some indicators of rice environmental health that signify favorable invertebrate diversity and biological control activity; and/or indicators that reveal the stability of the production system and the ecosystem health. These will prevent farmers from upsetting the balance by misusing insecticides or applying excessive nitrogen fertilizer. Therefore, it is necessary to develop simple tools designed to monitor the indicators which can be used by the rice farmers for pest management decision making.

VII.6. Regional analysis of irrigated rice ecosystems

Currently, the nature of invertebrate diversity and food web, and the ecosystem regulating services are only partially understood in the tropical Asian irrigated rice environment. It can only be assumed that these results may be applicable to the subtropical irrigated rice environments of Asia. No such research has been conducted in similar environments in other major rice growing areas such as Africa and Latin America. These basic studies are essential particularly for Asia where researches are being conducted under rainfed lowland environments, and intermittent wet and dry irrigation systems. The Asian experience will be very useful in conducting parallel investigations elsewhere in the world.

VII.7. Analysis of the irrigated rice vs. aerobic rice in relation to stability

Information on the invertebrate diversity, and ecosystem functions and services in relation to insect pest regulation in aerobic rice is virtually unknown; thus basic research on this is badly needed. In the aerobic rice system, invertebrate diversity will probably be lower because of the absence of an aquatic environment (rice paddies) which is known to have a rich invertebrate community with many generalist predators living on the water surface or in the water. Although invertebrate diversity in aerobic rice systems may be lower than that in the irrigated system, this does not mean that it has less pest regulation services.

In the face of a looming water crisis, an alternate wet and dry irrigation system is likely to replace some of the areas which are presently almost continuously flood irrigated. Research on the invertebrate diversity and ecosystem functions and services in this rice system will be essential to prepare for these future challenges.

VII.8. Main gaps in the scientific knowledge

VII.8.1. Quantifying biodiversity and ecosystem services

The matrix in Table 14 shows the enormous gaps in our knowledge of invertebrate diversity, and ecosystem functions and services for insect pest regulation. To date, there is only little understanding of this subject in the tropical irrigated systems of Asia, and much less information for the rainfed lowland crop with a gradient of hydrological situations. Data for rice grown in the subtropics and temperate areas is even less, and virtually none on upland (aerobic) rice. Research in these other major environments in Asia and other major rice growing regions, is necessary in order to acquire greater knowledge for developing sustainable rice production.

Reliable taxonomic identification of flora and fauna is an essential element of any research involving biodiversity. There is currently an acute shortage of taxonomists in the region, and taxonomic expertise and facilities are virtually absent in most major rice-producing countries. In the past, certain developed countries and international organizations provided taxonomic services to the developing world, either free or for a minimal fee. But the funding crisis either closed down or curtailed the activity of most of these services. For instance, IRRI’s rice arthropod taxonomic facilities and services were discontinued more than a decade ago, and the taxonomic services of the Commonwealth Agriculture Bureau International and the British Natural History Museum have also been stopped. This is a major stumbling block for biodiversity research in rice.

Therefore, there is an urgent need to develop manpower and facilities for taxonomic services for the developing world's rice-growing countries. Scholarships for advanced studies in taxonomy can be offered but it will take some time for such new investments to deliver. In the meantime, a provisional service can be implemented by forming a network of biodiversity researchers in the developing world which should include all available taxonomists. Recent developments in electronic communication technology may be another alternative. For example, the Plant Quarantine Department of Australia presently uses a system of remote microscopy wherein offices scattered over the country can be connected with the taxonomist through internet and remote microscopy. An officer at any point in the network can identify a specimen with the help of the central taxonomist who examines the specimen through the remote microscopy system. It is suggested that IRRI develop a similar hub of taxonomists for rice by tapping the rice research institutes of the major rice-growing countries.

VII.8.2. Valuation of ecosystem services in monetary values

Ecosystems are providing a significant service in pest regulation but to date, no specific value has been attached to the service. In order to promote the importance and value of ecological services, and make them understandable to policy makers, farmers and the general public; it is necessary to attach a definite monetary value to ecological services. Economists and social scientists need to get together with the biologists to carry out such an exercise.

VII.8.3. International collaboration

Most of the major rice-growing countries are 'developing' whose R and D often depends on external funding. Collaboration between these countries and the developed world is necessary for R and D in biodiversity research. Collaboration and funding are also needed for professional manpower development in the case of advanced researches requiring modern and sophisticated laboratory facilities. In the future, taxonomists in the developed world could also make a valuable contribution to biodiversity research through remote microscopy connectivity.

VII.8.4. Projected effects of climate change

Climate change is expected to raise carbon dioxide levels and temperatures, and increase the frequency of extreme climatic events such as storms, droughts, and heavy rainfall in monsoon climates that will increase the incidence of flooding. Rising sea levels are expected to increase flood risk and salinity intrusion in rice growing environments in Delta areas (Wassman et al, 2004). Simulations for the major rice-growing regions of Asia demonstrate that yield decreases by 7% for every 1ºC rise in temperature above the current mean temperature at existing atmospheric carbon dioxide concentration. Elevated carbon dioxide levels will increase yield by increasing dry matter production, number of panicles, and grain filling percentage (Ziska et al, 1997). However, the yield benefit due to the elevated carbon dioxide in rice will be cancelled out by the losses due to higher temperatures (Heong et al, 1995).

Temperature is the most important factor affecting insect ecology, epidemiology, and distribution (Heong et al, 1995). Some researchers speculate that higher temperature is likely to shorten pest life cycles so that an additional generation may occur in a crop season, thus increasing crop loss. However, higher temperature may shorten crop growth durations and counter balance the effect of higher temperature on pest life cycles. More studies on the effect of higher temperature and elevated carbon dioxide on rice invertebrates including pests and natural enemies, need to be undertaken to project the possible effects of climate change on rice pest management.

So far, very few attempts were made to examine how species would interact, evolve or adapt to global warming. A simplistic approach such as that based on temperature-driven models may give wrong predictions. The impact of global warming should depend on the genetic flexibility of the populations (Kareiva et al, 1993); and the distribution of tolerant phenotypes, migration patterns, and competition (Heong et al, 1995). A general trend may be obtained by comparing the food web structure of rice invertebrate populations (Cohen et al, 1994) in environments with high temperature extremes (Heong et al, 1995). Monitoring the distribution and spread of stress tolerance in invertebrate species may provide useful information for predictions.

In a nutshell, relevant data on possible responses of rice invertebrate communities to global warming are limited. Any predictions made from such limited studies may be grossly erroneous. However, studies do indicate the flexibility inherent within species as well as in the invertebrate communities. Since species do not encounter global warming in isolation, community-level or ecosystem-level responses to the changes must be investigated (Heong et al, 1995).

VII.9. Priority action

VII.9.1. Strengthening and harmonizing pesticide registration and marketing

The absence of the need to apply insecticides in most Asian rice fields has been shown. In fact, the indiscriminate routine application or the abused use of insecticides has been identified to be the root cause of the loss of invertebrate biodiversity and ecosystem services in rice production systems. This precipitated the wave of planthopper outbreaks during the 1970s and 2000s which cost individual farmers dearly and led to food grain shortfalls of millions of tons. Numerous experiments have proven that insecticide applications contribute to the creation of secondary pests particularly the planthoppers which seriously reduce yields, pollute the environment and render rice production systems unsustainable. This is mainly because insecticides disrupt the ecosystem services resulting in complete failure of the biological regulation of insect pests.

The question of the possibility to revive such a disoriented ecosystem service now arises. The answer is a definite yes. Pesticides were intensively applied at the IRRI research farm in Los Baños, Philippines from the 1960s when pest outbreaks were frequent and damaging. In 1993, however, pesticide applications were dramatically reduced and within a few years, the full ecosystem service had reestablished itself (Table 15), and pest outbreaks subsided.

Another interesting example is from a farmer's experience in the Philippines. It was found that Mr. Masajo of Barangay San Felix in Laguna Province had successfully grown two rice crops per year for 30 years on his 20-hectare farm totally without the use of insecticides (Islam and Heong, 1999a). This farmer not only saved from not buying insecticides but his yields also became higher than those of his neighbours and even the average yield in the entire province.

Although the Farmer Field School training and participatory research taught farmers the practical elements of IPM and reduction of their own insecticide use, they later succumbed to aggressive pesticide marketing and went back to their old ways. Thus, farmer training and IPM experience are often not enough to stop pesticide abused use. In order to effectively curb the misuse of pesticides, it is important to implement appropriate regulations for pesticide registration and marketing.Vietnam is taking an initiative in the governance of pesticide marketing and protecting farmers from vicious marketing campaigns in recent years. Other countries also need to pursue similar and other initiatives. International organizations such as FAO could promote/foster dialogue between countries to strengthen the regulatory management of pesticides for risk reductions. FAO and IRRI jointly supported the pest control resolution on review, revision and/or formulation of national policies for the regulation and use of pesticides in rice production which was adopted during the recently concluded convention of the Ramsar International Wetlands Conservation (COP-XI-DR15) in July 2012. Such issues may be considered within the framework of international agreements and organizations such as the Asia and Pacific Plant Protection Commission and ASEAN/SAARC for the implementation of the International Code of Conduct on Distribution and Use of Pesticides.

VII.9.2. Accreditation of plant protection service providers

In Asia, pesticide dealers/retailers play a major role in pesticide application decision making. In Southeast Asia, pesticides are sold in grocery stores along with all the usual items including foods. In some countries such as Bangladesh, the same retailers sell fertilizers and pesticides. Retailers who have no expertise in crop production or pest management, often convince the farmer to take some pesticides along with the fertilizer he buys. Even worse, some farmers run to the pesticide retailer for suggestions when he perceives that he is facing a pest problem. Thus, retailers play a very important role in pesticide application decision making.

This situation obviously needs to be changed at the grassroot level. The Bangladesh Department of Agriculture trains the “grassroot”- agricultural agents who report to their supervisors with agricultural bachelor degrees. The responsibility of recommending pest management services, including pesticide use can only be given as a last resort to the department’s grassroot level personnel. Without their prescription, retailers should not be allowed to sell pesticides to anyone. Such an arrangement will help to deter pesticide abused use and subsequently reduce the deleterious effect on invertebrate diversity and ecosystem services.

Pesticides are usually applied in rice by untrained persons and often at the wrong time using an inappropriate applicator. Policy interventions are needed so that pesticides can only be applied by trained and certified personnel. Along with this, pesticide application training should be provided, and certification facilities, be developed.

FAO is currently supporting the development of a licensing and inspection system for the pesticide retail sector in Cambodia and Lao PDR under Project GCP/RAS/229/SWE. Lessons learned from this work could potentially be used to help strengthen similar systems in other countries in Asia and beyond. FAO is also developing various specifications and guidelines for the implementation of the International Code of Conduct on Distribution and Use of Pesticides through the FAO/WHO Expert Panel. In addition, the FAO Regional Office for Asia and Pacific has developed five operational guidelines for Southeast Asian countries through a regional technical cooperation program (TCP) to promote regulatory pesticide management among ASEAN countries. This will hopefully lead to the preparation of country action plans for follow up actions in the enhancement of regulatory management of pesticides in Southeast Asian countries.

VII.9.3. Funding biodiversity research

Most of the major rice-producing countries are still ‘developing’ and lack funds for biodiversity research. In the past, international agencies (and sometimes pesticide companies) funded pest management research in the developing countries. However, pesticide companies will usually not be interested in funding biodiversity research because it will very likely be contrary to their commercial interests. Therefore, the commitment of international agencies and environmentalist groups or organizations to support R and D initiatives including manpower development in ecology, production, biology and taxonomy, will be very crucial.

VIII. Conclusions

The Earth’s equilibrium appears to be maintained through ecological processes in which biodiversity plays a central role (Benckiser and Schnell, 2007). There are virtually no ecosystems in the world that are “natural” in the sense of ‘escape from human influence’. The needs of human populations for food, fuel and fiber have historically been supported directly or indirectly by genetic diversity among the microorganisms and invertebrates. These organisms perform functions which prime and fuel the metabolism of soils, plants and animals. The development of sustainable agro-ecosystems and the enhancement of agricultural productivity increasingly depend on the maintenance of such diversity for: a) the improvement of soil structure and fertility through the decomposition of organic materials added to the soil, and the detoxification of pesticides and other pollutants; b) the provision of biological control for pests and diseases of plants and animals; c) processing and enhancing the nutritional value of foods; and d) maximizing the potential of novel products for use in the pharmaceutical and other industries (Hawksworth, 1991). Among these ecological services, invertebrates are particularly involved in the improvement of soil structure and fertility, crop pollination, and biological control of pests of plants and animals.

So far, most of the attention has been focused on the loss of biodiversity among vertebrates and higher plants where changes in habitat produce easily observed losses in the diversity of species present. Actual losses in numbers of species are likely to be much greater among the less readily observed invertebrates; the small, cryptic species living in the soil within the crop fields and forest canopy. Biodiversity among invertebrates is extremely important for sustainable agricultural production in general (Hawksworth, 1991).

Invertebrate diversity in rice production systems is seriously threatened by the abused use of pesticides especially insecticides. In order to utilize ecosystem services for sustainable rice productivity, the following are required: a) conservation of the existing genetic potential in invertebrates; b) elimination of man-made causes that affect invertebrate diversity and abundance such as misuse of pesticides; c) research on the measurement of the diversity of organisms, and d) identification of the ecological interactions and the role played by different invertebrates in rice production systems.

In order to utilize the ecosystem services in rice production, policy interventions as well as research and development (R and D) are necessary.

VIII.1. Policy interventions

It is apparent that invertebrates play a crucial role in keeping insect pest populations below the economic injury level, and serious pest outbreaks occur when the ecosystem services provided by the complex of invertebrates are disturbed by insecticides, and to a lesser extent by excessive nitrogen use. In order to keep rice production systems sustainable, the abused use of pesticides especially insecticides must be halted.

Massive efforts to reduce insecticide use through improving farmers' knowledge and decision- making skills during the 1980s and 1990s have shown that although participating farmers reduce their insecticide use, they ultimately succumb to aggressive pesticide marketing campaigns. Thus, legislative control of pesticide registration and marketing will have to be implemented in order to curb the misuse of insecticides in rice and other crops. Vietnam is taking a lead in the governance of pesticide marketing and in preventing farmers from being the victims of marketing campaigns. Although the control of pesticide marketing is still at the primary stage, positive signs are already visible in Vietnamese rice production systems.

The following policy interventions are suggested for immediate consideration:

- Control pesticide marketing campaigns by revising all relevant legislation, rules and laws (perhaps along the lines of the pharmaceutical industry). In this endeavor, the following points should be considered: a) banning of pesticide advertisements ; b) reduction in number of retailers; c) prohibition of pesticide retailers from selling food items and fertilizers in the same shop; d) introduction of a prescription system for pesticide procurement by the farmer; and e) making provision for the punishment of those who market banned pesticides; and f) introduction of legislation on operator certification and equipment registration/inspection
- In order to educate the general public and future generations about the need for sustainability of rice production systems, introduce IPM and Ecological Engineering at the high school level; and train at least one teacher from each school on these topics.
- Empower the grassroot level agriculture department personnel by introducing IPM and
- Ecological Engineering into agriculture training curricula.
- Employ the electronic mass media (TV and radio) to mobilize farmers and the general public in favor of IPM and Ecological Engineering.

VIII.2. Research and development

There is growing recognition of the need for a better understanding of the ecosystem services in the rice environment. Although some methodologies have been developed to measure and estimate the different pest regulation services, the quantification of some services such as predation and the attachment of a precise value to the services, is still a major challenge. Many countries lack relevant data at the appropriate geographic level. Basic knowledge of the functional role of many invertebrates in agricultural and other ecosystems including rice, is totally inadequate. A major research effort is needed to assess the importance of biodiversity, improve its management, and deepen the general understanding of how it supports the stability of rice ecosystems.

The following recommendations are proposed:

- Monitoring of pesticide and nitrogen fertilizer use, and the incipient development of pesticide resistance.
- Regular monitoring of the pest and natural enemy situation.
- Studying invertebrate diversity and abundance, and food web structure and functions in upland rice, rainfed wetlands, and wet and dry irrigation systems in Asia and elsewhere.
- Establishing ecosystem engineering sites at all research stations and agriculture training institutes for demonstration to agricultural trainers and high school teachers.
- Increase the rice genetic (varietal) diversity in the field through the development and introduction of additional modern varieties for the different rice environments.
- Study impact of aerobic and no-till rice systems

VIII.3. International support

In the developing countries, R and D primarily depends on external funding. Some of these countries also lack high quality education systems. External funding will be required to assist in the following aspects:

- Invertebrate bio-diversity research in rice production systems
- Manpower development especially in the field of taxonomy, ecology, production, biology
- Development of laboratories and equipment for taxonomic identification
- Development of a taxonomic network using a remote microscopy system like the one developed and practiced in Australia

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