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Chapter 2.5

# Rice pest management: issues and opportunities

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## Introduction

Rice fields are managed ecosystems in which a large diversity of floral, faunal, and microbial species provides a wide range of services for human well-being (MEA 2005). Most of these species do not reduce production; indeed, many are beneficial, such as predators, parasitoids, flowering plants, and soil bacteria. However, a few species become pests, that is to say, they are responsible for crop losses exceeding acceptable thresholds, mostly when they occur in high densities. They then can affect production and threaten food security. Although much of the literature on crop losses has focused on biomass (yield) loss, comparatively little research has dealt with qualitative losses (Savary et al 2006a). Qualitative losses include quarantine diseases, which prevent seed sales, and, more importantly, diseases that produce toxins that affect food safety. In many cases, pest species, especially insects, are regulated by the diversity of natural enemies associated with agroecosystems. The most important ecosystem service that rice cultivation provides to humans is food provisioning (MEA 2005). In many societies, especially in Asia, rice also provides a key cultural service as well. The regulatory systems that support ecosystem services, if properly managed, can continue to sustain these services for centuries.

The Green Revolution that began in the 1960s triggered a cascade of technological events in plant protection. In particular, pesticide use on rice, especially insecticides, increased with the adoption of rice varieties that lacked resistance to many pests (animal pests and pathogens). Recommended technology packages for rice in the 1960s and ’70s usually included insecticides, especially organochlorines. These insecticides not only killed insect pests, but their natural predators as well. Natural regulation of pests in rice ecosystems was disrupted, creating a favorable environment for pest species such as planthoppers. By the 1980s, insecticide resistance became an increasing problem, especially for organophosphates and carbamates that were replacing organochlorines. Farmers responded by increasing dosages or by combining several chemicals in toxic mixtures. As a result, even more natural predators were killed, insecticide resistance buildup was accelerated, and human health and the environment were further threatened. Other factors affecting the resilience of rice ecosystems have been associated with measures taken to increase rice production profitability, such as year-round cultivation of rice on the same land (creating favorable conditions for pest outbreaks) and higher nitrogen applications to the higher-yielding rice varieties (enhancing their susceptibility to some pathogens and insects).

It became clear that alternative approaches to rice pest management were needed. With respect to key rice diseases, rapid progress was made to develop varieties with

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suitable resistances (Jena and Mackill 2008, Zeigler and Savary 2009) and in many cases, particularly resistance to diseases, these varieties were successful (Bonman et al 1992, Jena and Mackill 2008). Governments began to rethink the need for policies to subsidize pesticide use. They also began to tighten pesticide regulations and enforce them more strictly in several rice-growing countries. Integrated pest management (IPM) approaches were developed that encouraged farmers to restrict their use of pesticides to situations when economic loss might be expected (Teng 1994).

However, several forces have combined to keep pesticide use relatively high on rice despite growing evidence that pesticide applications, at least for insects and diseases, can often be counterproductive due to the adverse effects on beneficial organisms and the natural balance:

1. Farmers, policymakers, and other officials have grown accustomed to applying pesticides as “medicine” to cure pest problems, in many cases as preventive medicine, and as “insurance” against injuries (Zadoks 1985), “problems” that may in fact cause little yield loss.
2. Driven by an understandable motive for profit, chemical companies run intensive marketing campaigns led by a cadre of salespeople who are a constant presence in rice-growing areas.
3. As farm wages have increased due to economic growth in Asia, herbicides have increasingly been substituted for hand weeding (Naylor 1996), a trend necessitated by the transition from transplanting to direct seeding of rice (Pandey and Velasco 2005). In Asia, approximately 20% of the rice area is direct seeded though local variation is considerable: almost all of southern Vietnam and the Malay peninsula are direct seeded, while transplanting predominates in Indonesia and Bangladesh. Weeds are the cause of the highest chronic yield losses in rice (Savary et al 2000b).
4. IPM approaches are often information-intensive, and few countries have applied innovative low-cost methods for reaching large numbers of farmers with IPM messages on a continual basis. Without such methods, the frequent repetitive messages from chemical companies predominate and cause discontinuance of learned practices (Escalada et al 2009).
5. The main rice varieties grown over large areas are still susceptible to pests or varietal resistance can be overcome despite continual progress in breeding multiple resistance in cultivated rice varieties (Bonman et al 1992, Jena and Mackill 2008). High insecticide use tends to speed up resistance breakdown in varieties (Gallagher et al 1994). In the 1990s, farmers in Vietnam used mainly organophosphates and carbamates, which remained dominant (35% of sprays) in the 2000s (Escalada et al 2009). It has been shown that, by reducing insecticide use, especially in the early crop stages, natural enemy biodiversity would return to rice fields in sufficient quantity to manage insect pests (Heong et al 2008). But some still question this conclusion, including policymakers who affect national pesticide policies.

The future of pest management in rice, however, holds promise for reduced pests and eventually reduced pesticide use. Plant breeding will become more efficient

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as molecular-assisted breeding speeds up the process for breeding in pest resistance, and as IPM becomes more widespread with improved practices, enhanced methods for disseminating information to farmers, and corresponding support policies. Ecological engineering techniques (Gurr et al 2004, Gurr 2009) may help to conserve or restore regulatory ecosystem services to reduce pest problems in rice. In some cases, genetically modified organisms (GMOs) may play a significant role in reducing pest problems and pesticide use. China, for example, has given biosafety approval for *Bt* rice for the control of the rice-borer pest, and approval for large-scale commercial release can be expected in 2–3 years (IRRI 2010). This is expected to result in a large-scale reduction in insecticide use, although some believe that pesticide use by Chinese farmers is influenced as much by perception as by pest pressure. Thus, a significant reduction in insecticide use may depend on a concurrent strong stewardship program aimed at insecticide reduction (Heong and Escalada 2007b, Cohen et al 2008).

This chapter provides an overview of the pest management situation in rice and the factors that will influence the use of alternative pest management practices in the future. We examine rice pests and losses; pesticide use on rice; economic, environmental, and health impacts of pest management practices on rice; policies and regulations that influence pesticide use and alternative pest management practices; and the potential for IPM and biotechnologies to play larger roles in future rice pest management.

## Rice pests and losses

### Rice pests

A large variety of insects (more than 100) feed on rice, although most are not economically damaging enough to require any management practices. The rice plant has strong compensatory abilities to recover from such injuries (Rubia et al 1996) if they occur in the vegetative stage. The relative importance of rice insect pests varies from country to country, although the planthoppers—brown planthopper (BPH), *Nilparvata lugens*; the whitebacked planthopper (WBPH), *Sogatella furcifera*; and small brown planthopper (SBPH), *Laodelphax striatellus*—affect most rice-growing areas. Major rice-producing countries such as China, Vietnam, India, and Thailand have recently experienced serious problems (see http://ricehoppers.net/). Several stem borers and leaf-feeding insects are also found in most rice-growing areas. Stem borer species such as the yellow stem borer (YSB), *Schoenobius incertulas*, and the striped stem borer (SSB), *Chilo supressalis*, can sometimes cause major yield losses. The YSB is dominant in most tropical and subtropical areas, while the SSB occurs mainly in temperate rice. Leaf feeders, such as the rice leaf folder (RLF), *Cnaphalocrocis medinalis*, often attack rice in the early crop stages, causing highly visible leaf injury, but, because of plant compensation, the injury often does not translate into a yield loss (Graf et al 1992).

A wide range of rice diseases affect rice (Ou 1987), among which blast, sheath blight, bacterial blight, brown spot, and several virus diseases, including rice tungro, are of primary concern. As with insect pests, rice diseases can be categorized as

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chronic yield reducers (e.g., brown spot and sheath blight), whereas other diseases cause sporadic, often large-scale, and extremely damaging epidemics (e.g., blast and most virus diseases; Zeigler and Savary 2009). Such uncertainty of risk adds another layer of complexity to assessing priorities and developing sustainable decision-making processes, from the field to the national scales.

A broad spectrum of weeds (Moody 1991) is present in all rice-growing areas. For example, 140 species are commonly associated with direct-seeded rice (Rao et al 2007) and the grasses, such as *Echinochloa* species, are a major constraint on rice worldwide. In aerobic rice cultivation, nematodes are considered an emerging problem.

Although few data are available, rodents are also a problem for cereal production (Stenseth et al 2003, Meerburg et al 2009), and are thought by many to cause 5–10% preharvest rice production losses in Asia (Singleton 2003). The highest chronic rice losses due to rodents are in Indonesia; in West Java, mean annual losses are estimated at about 17% (Singleton et al 2005). Family rice plots are small, and it is not uncommon for farmers or villagers to lose half of their entire rice crop to rats. Occasionally, especially in upland rice environments, rodent populations erupt, with dramatic effects on highly vulnerable and food-insecure families. Accurate estimation of losses due to rodents is complicated by the fact that damage is patchy in space and time. The sporadic nature of losses may account for the wide differences in estimates. For example, the RICEPEST model places them at less than 1% (Table 1).

### Crop losses

Crop loss assessment is a research field in its own right, and information on crop losses, even for such a major crop as rice, is patchy for several reasons. First, crop losses are derived from both direct and indirect effects. Indirect effects include losses in quality as well as indirect economic losses (Chiarappa 1971). Second, quantitative yield losses due to pests such as insects, diseases, and weeds are not additive, especially in rice (Padwick 1956, Pinstrup-Andersen et al 1976). Third, observed injuries do not necessarily translate into quantitative yield losses (Savary et al 2006a), as plants can compensate, especially for foliar damage early in the season. Fourth, in most cases, a crop is exposed to not one but several injuries during the season, resulting in a crop health syndrome (Savary et al 2006b), that is to say, a combination of injuries due to diseases and insects encountered by a crop during its cycle in a given production context. Crop health syndromes depend on production situations, as demonstrated in a range of agroecosystems, including rice-based systems (Savary et al 2006a). Since production situations evolve rapidly, so do crop health syndromes, and thus the importance of specific pests.

Because of these factors, yield loss estimates differ considerably from one source to another. Oerke (2006) estimates global crop losses in rice due to weeds, animal pests, and diseases at 10.2%, 15.1%, and 12.2% of the attainable yield, respectively. It is worth noting that these estimates were derived from pesticide industry estimates, with the result that (1) some "pests"—diseases, weeds, animal pests—tend to be

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**Table 1. Estimated yield loss due to rice pests under current conditions, and estimated yield gain due to the application of pest management tools based on the RICEPEST simulation model.**

| Item | Current estimated yield loss | | Estimated yield gain due to available pest management tools[a] | |
|---|---|---|---|---|
| | Absolute[a] (t/ha) | % | Absolute[b] (t/ha) | % |
| Injury profile[c] | 1.4–2.3 | 25–43 | 1.2–5.7 | 16–69 |
| Bacterial blight | 0–0.03 | 0–0.6 | 0–0.9 | 0–17 |
| Sheath blight | 0.3–0.7 | 5–10 | 0–2.4 | 0–29 |
| Brown spot | 0–0.5 | 0–10 | 0 | 0 |
| Leaf blast | 0–0.1 | 0–1.7 | 0–3.5 | 0–65 |
| Neck blast | 0–0.1 | 0–2.1 | 0–2.1 | 0–40 |
| Sheath rot | 0.1–0.4 | 1.3–7.3 | 0 | 0 |
| Brown planthopper | 0–0.01 | 0–0.3 | 0.1–0.3 | 0.8–5.3 |
| Defoliating insects | 0.01–0.05 | 0.2–0.9 | 0–0.1 | 0.1–0.9 |
| Deadhearts (stem borers) | 0.02–0.05 | 0.3–1.0 | 0.02–0.12 | 0.3–2.3 |
| Whiteheads (stem borers) | 0.1–0.3 | 1.9–5.8 | 0.1–0.7 | 1.9–13.2 |
| Weeds | 0.7–1.2 | 12–22 | 0.5–3.1 | 9–51 |
| Snails | | Trace* | | |
| Rats | | Trace* | | |
| Birds | | Trace* | | |

[a]Simulated gains, relative to current attainable yields, from applying available management tools, including host-plant resistance, crop management, and pesticides. [b]Estimates are provided as ranges across prevailing production situations. [c]Injury profile refers to the combination of injuries caused by weeds, diseases, insects, and animal pests, occurring during a cropping season in a given production situation. *Trace: indicates less than 1% relative yield loss in the [production situation * injury profile] combination, where the mode of corresponding injury is the highest.
Source: Willocquet et al (2004).

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overrepresented (pesticide trials do not report nonsignificant results on an individual yield-reducing agent), (2) interaction among yield-reducing agents is ignored, and (3) yield-reducing agents for which no pesticide exists (or for which pesticide use is deemed unprofitable by the chemical industry) are ignored (Savary et al 1998). An example of the latter is rice brown spot (*Bipolaris oryzae*), the “poor farmers’ field disease,” which causes severe and chronic losses in South and Southeast Asia (Savary et al 2000a, b).

The complexity involved in estimating crop losses suggests the need to develop a modeling approach. RICEPEST (Willocquet et al 2004) is specifically designed to address this need. It capitalizes on long-term, widespread surveys (Savary et al 2000a) and experiments (Savary et al 2000b) conducted by the International Rice Research Institute (IRRI) and its partners. Modeling also enables us to estimate gains from applying pest management tools. A summary of estimated yield losses and gains due to the use of pest management tools is provided in Table 1. These results pertain to tropical Asian lowland (irrigated and rainfed) ecosystems.

## Pesticide use on rice

Data on rice pesticide sales for various countries are difficult to obtain given their proprietary nature, but some data are available for the period 1980-96 from IRRI (at http://beta.irri.org/solutions/index.php?option=com_content&task=view&id=250), and a few estimates are available for more recent years. Summarized sales data presented in Tables 2–5 indicate that sales of all pesticides (i.e., insecticides, fungicides, and herbicides) grew over time in most countries until the mid-1990s, but have generally stagnated or recently declined, especially in real terms (removing inflation). Fewer pesticides are being used now, but on a larger area (especially for herbicides), and the introduction of products with higher biological activity and lower application rates means that the amount of pesticides per hectare has declined. Data in Table 2 must be interpreted with caution as the 2007 data are available at the distributor level while data for earlier years are at the grower level. In an attempt to make them comparable, the distributor-level data were multiplied by a 25% markup. Markups vary by chemical, however, and therefore these data should be viewed as only approximate. Other evidence also indicates that there may have been a decline in rice pesticide sales in the late 1990s and an upward trend again from 2001 to 2007. In summary, pesticide use roughly doubled from 1980 to 1996 but has leveled off since then in real terms.

Pesticide application per hectare varies dramatically by country. Japan, with only a little over 1% of the rice area planted, used a third of all pesticides in 2007. However, that proportion is down from around half in earlier years, with pesticide use in China, Republic of  Korea, and India growing substantially over time. In addition, pesticide prices may differ by country, and are likely to be lower in China than in Japan, for example. Therefore, the increase in pounds of active ingredient in China may be even larger than the sales data suggest.

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Rice herbicide sales (Table 3) show that Japan is still the dominant leader, but China, Republic of Korea, the United States, and Brazil have moved up substantially. On a percentage basis, India has seen its herbicide sales grow rapidly, but it was starting from a small base and it applies less per hectare than most other countries. India has more rice hectares than any other country, with 44 million ha in 2007. The United States has seen its rice herbicide sales drop substantially since the mid-1990s. Overall, herbicide sales have increased as a proportion of total pesticide sales, primarily due to growth in countries such as China that have experienced rising and higher labor costs for hand weeding. One reason the overall market has been stagnant is that the rice area cultivated in Japan and Republic of Korea has declined following an opening up of their markets following international trade negotiations.

Japan has the largest share of the rice insecticide market (Table 4), but its dominance is less than it is for herbicides and fungicides and its share has been declining since the late 1980s. The shares of China and India have grown, with the possibility that China may overtake Japan as the leading insecticide-using country in the future. Republic of Korea and India are the only countries besides China and India with more than US$100 million in sales. In real terms, rice insecticide sales have declined gradually since the late 1980s. Insecticide sales are volatile in individual countries from year to year due to the sporadic nature of certain insect outbreaks.

Japan dominates the rice fungicide market (Table 5) but its share has declined steadily from more than 60% in 1980 to 40% in 2007, due in part to the decline in rice area. Fungicide sales in China, Republic of Korea, and India have grown, although the market is smaller across the board than it is for herbicides and insecticides.

## Costs associated with pesticide use on rice

Pesticides are often applied on rice in Asia from two to eight times per season (Huang et al 2003) and make up 2% to 7% of the value of gross production (Table 6). Huang et al (2003) found that pesticides accounted for 7–8% of input costs on rice in China. The relatively low cost of pesticides in relation to farmers' perceptions of potential production losses is a major factor explaining current pesticide usage. The available yield loss data illustrate this point. Current pest management practices, which are heavily dependent on pesticides for managing insect pests and many diseases, still result in yield losses of approximately 10–15%, but losses would be much higher without pest management. Similarly for weeds, losses are about 15–20% under current weed control and would be much higher otherwise. The wide gap between current and potential yield losses for weeds is of concern because current weed control practices in many areas often involve hand weeding. As noted above, as labor costs continue to rise, we can expect an increase in herbicide use.

Four major hidden costs are not reflected in the direct economic costs of pesticide use. The first is the cost associated with the long-term buildup of resistance to pesticides, the second is the effect that pesticides can have on natural predators of pests, the third is the acute and chronic effects of pesticide exposure on human health, and the fourth is the long-term effects of pesticides on other ecosystem services.

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**Table 2. Global rice pesticide (insecticide, fungicide, herbicide) sales (million 2000 US$), selected years.**[a]

| Region | 1980 | 1988 | 1996 | 2007 |
|---|---|---|---|---|
| Japan | 700 | 1,849 | 1,636 | 1,043 |
| China | 120 | 251 | 430 | 400 |
| Republic of Korea | 61 | 205 | 405 | 290 |
| India | 89 | 219 | 225 | 244 |
| Vietnam | 19 | 34 | 44 | 123 |
| United States | 117 | 115 | 229 | 113 |
| Brazil | 81 | 95 | 93 | 113 |
| Rest of world | 387 | 587 | 542 | 800 |
| Total | 1,574 | 3,355 | 3,607 | 3,125 |

[a] Sales data at the grower level in nominal prices for the years 1980, 1988, and 1996 were obtained from IRRI (http://beta.irri.org/solutions/index.php?option=com_content&task=view&id=250). For 2007, the data in nominal prices were obtained from Phillips McDougall AgriService at the distributor level and adjusted by a 25% mark-up to approximate grower-level values. Nominal data were subsequently deflated using International Monetary Fund GDP price deflator for the United States to convert the series in terms of constant prices at year 2000.

**Table 3. Global rice herbicide sales (million 2000 US$), selected years.**[a]

| Region | 1980 | 1988 | 1996 | 2007 |
|---|---|---|---|---|
| Japan | 459 | 753 | 703 | 490 |
| China | 19 | 11 | 51 | 125 |
| Republic of Korea | 15 | 37 | 117 | 84 |
| India | 15 | 26 | 28 | 50 |
| United States | 78 | 81 | 194 | 86 |
| Brazil | 37 | 42 | 75 | 73 |
| Rest of world | 119 | 219 | 196 | 436 |
| Total | 741 | 1,169 | 1,363 | 1,343 |

[a] Sales data at the grower level in nominal prices for the years 1980, 1988, and 1996 were obtained from IRRI (http://beta.irri.org/solutions/index.php?option=com_content&task=view&id=250). For 2007, the data in nominal prices were obtained from Phillips McDougall AgriService at the distributor level and adjusted by a 25% mark-up to approximate grower-level values. Nominal data were subsequently deflated using International Monetary Fund GDP price deflator for the United States to convert the series in terms of constant prices at year 2000.

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**Table 4. Global rice insecticide sales (million 2000 US$), selected years.**[a]

| Region | 1980 | 1988 | 1996 | 2007 |
|---|---|---|---|---|
| Japan | 241 | 594 | 419 | 253 |
| China | 102 | 196 | 213 | 204 |
| Republic of Korea | 46 | 86 | 154 | 105 |
| India | 74 | 169 | 154 | 146 |
| Indonesia | 33 | 99 | 46 | 23 |
| Rest of world | 337 | 236 | 228 | 314 |
| Total | 833 | 1,380 | 1,214 | 1,073 |

[a] Sales data at the grower level in nominal prices for the years 1980, 1988, and 1996 were obtained from IRRI (http://beta.irri.org/solutions/index.php?option=com_content&task=view&id=250). For 2007, the data in nominal prices were obtained from Phillips McDougall AgriService at the distributor level and adjusted by a 25% mark-up to approximate grower-level values. Nominal data were subsequently deflated using International Monetary Fund GDP price deflator for the United States to convert the series in terms of constant prices at year 2000.

**Table 5. Global rice fungicide sales (million 2000 US$), selected years.**[a]

| Region | 1980 | 1988 | 1996 | 2007 |
|---|---|---|---|---|
| Japan | 381 | 502 | 514 | 259 |
| China | 64 | 45 | 67 | 66 |
| Republic of Korea | 44 | 82 | 133 | 99 |
| India | 24 | 24 | 43 | 48 |
| United States | 0 | 5 | 28 | 19 |
| Rest of World | 96 | 79 | 142 | 150 |
| Total | 609 | 737 | 927 | 643 |

[a] Sales data at the grower level in nominal prices for the years 1980, 1988, and 1996 were obtained from IRRI (http://beta.irri.org/solutions/index.php?option=com_content&task=view&id=250). For 2007, the data in nominal prices were obtained from Phillips McDougall AgriService at the distributor level and adjusted by a 25% mark-up to approximate grower-level values. Nominal data were subsequently deflated using International Monetary Fund GDP price deflator for the United States to convert the series in terms of constant prices at year 2000.

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**Table 6. Pesticide use on rice at selected sites in Asia (1994-99).**

| Site | Insecticides (kg a.i./ha/season) | Herbicides (kg a.i./ha/season) | Others (kg a.i./ha/season) | Total (kg a.i./ha/season) | Pesticide costs as a percentage of gross value of production |
|---|---|---|---|---|---|
| Tamil Nadu, India | 0.29 | 0.11 | 0.01 | 0.41 | 0.5 |
| Central Luzon, Philippines | 0.18 | 0.34 | 0.18 | 0.70 | 2.3 |
| Mekong, Delta, Vietnam | 0.51 | 0.49 | 0.10 | 1.10 | 3.8 |
| Red River Delta, Vietnam | 0.61 | 0.65 | 0.34 | 1.60 | 2.5 |
| West Java, Indonesia | 0.62 | 0.69 | 0.54 | 1.85 | 4.4 |
| Central Plain, Thailand | 0.97 | 0.89 | 0.25 | 2.10 | 7.0 |
| Zhejiang, China | 3.96 | 0.09 | 0.17 | 4.23 | 3.0 |

Source: Dawe D. The Second Green Revolution – trends and implications in pesticide use, IRRI Rice Knowledge Bank, www.knowledgebank.irri.org/ipm/index.php/pesticide-use-revolution-crop-health-2739/251-the-costs-of-pesticide-use.

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### Pesticide resistance and ecosystem disruption

The buildup of pesticide resistance over time can lead farmers to apply larger amounts of more toxic chemicals to manage pest outbreaks. Planthopper populations in China and Vietnam, for instance, have developed more than 200-fold resistance to some insecticides such as the neonicotinoids (Matsumura et al 2009). The negative effects on natural predators cause an ecological imbalance that leads to pest outbreaks. Insecticides that have adverse effects on nontarget beneficial arthropods such as bees, spiders, parasitoids, and aquatic fauna lead to a phenomenon in the ecosystem called "catastrophic synchronization" (Waage 1989). This phenomenon causes not only high predator mortality but also a disorganization of the food web structure, thus rendering predators ineffective (Heong and Schoenly 1998). For example, in the 1980s, excessive pesticide use decimated insects that preyed on brown planthoppers and disorganized the food web structures in Indonesia, resulting in a serious outbreak of planthoppers (Dawe 2002). Similar outbreaks routinely affect about a million ha in China every year (Cheng 2009).

Planthopper outbreaks are affected by the amount, timing, and types of pesticides that decimate BPH natural enemies (Heong 1996). BPH outbreaks have occurred recently in Thailand, China, and India (Heong 2009). Secondary pest problems occur after pesticides have been applied to control a different pest early in the season. Broad-spectrum pesticides are often applied that are highly toxic to bees, parasitoids and predators, and aquatic fauna. Examples of these chemicals are chlorpyrifos, cypermethrin, and avemectin. Their effects on causing planthopper outbreaks have been widely documented and discussed (Heong and Schoenly 1998 and Way and Heong 1994 provide reviews).

Buildup of resistance to chemicals is also a problem with weeds. Across all crops, 341 herbicide-resistant biotypes in 194 species have been reported (weedscience.org 2009). Although herbicide resistance in rice weeds in Asia lags behind other areas, possibly due to continued use of hand weeding and cultural practices such as flooding, several instances of resistance have been reported. Repeated herbicide application can also disrupt rice ecosystems and alter weed species composition, rendering the herbicides less effective. For example, in wet-seeded rice in Malaysia, application of 2,4-D resulted in the dominance of the grass *Echinochloa crus-galli,* whereas applying graminicides (e.g., quinclorac, pretilachlor, or propanil) promoted *Monochoria vaginalis* (Man and Mortimer 2002). Likewise, repeated applications of benthiocarb and propanil, over four seasons, led to the elimination of *E. crus-galli* but increased the proportion of *Scirpus* spp. sedges.

### Impacts on human health and the environment

Acute and chronic health problems associated with pesticide use on rice have been well documented (Rola and Pingali 1993, Pingali et al 1994, Pingali and Roger 1995, Antle and Pingali 1994, Dasgupta et al 2006, Devi 2007). IRRI assessed the health and environmental costs of using pesticides in rice production in the Philippines and found them to exceed the economic benefits (Rola and Pingali 1993, Pingali and

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Roger 1995). Applicators suffer acute and chronic health problems that reduce rice productivity. The major concern about pesticide use on rice is misuse as much as overuse, in other words, applying the wrong pesticide at the wrong time in the wrong amount with inadequate applicator protection. Clinical studies conducted on rice and vegetable farmers in Indonesia, the Philippines, and Vietnam found that most of the farmers exposed to pesticides experienced at least one negative health effect (Rola and Pingali 1993, Antle and Pingali 1994, Kishi et al 1995, Xuyen et al 1998). In Bangladesh, 37% of the farmers using conventional pest management reported health problems such as eye irritation, headaches, dizziness, vomiting, shortness of breath, skin effects, and convulsions (Dasgupta et al 2006).

Rice paddies include a vast array of vertebrate and invertebrate organisms (Pingali and Roger 1995). Major vertebrates include fish, frogs, and rats, while invertebrates include crustaceans, micro-crustaceans, aquatic insects and insect larvae, snails, worms, algae, and bacteria. The rural poor depend on consuming fish, shrimp, and other organisms from rice paddies, while nutrient recycling occurs in paddy soils through interactions among micro- and macro-organisms (Pingali and Roger 1995). Therefore, these organisms must be in balance to maintain human nutrition and soil fertility.

Pesticide use has numerous effects in the food chain associated with rice production, including effects on species number, relative composition of species, and residue accumulation in surviving populations. Pingali and Roger (1995) draw on the literature and detail those effects. The following is a brief summary of pesticide effects, based on their results: (1) the number of aquatic vertebrates declines rapidly with pesticide use; (2) pesticide residues in surviving populations of vertebrates tend to be low; (3) invertebrate populations suffer relatively small effects due to a reduction in predator populations such as fish and frogs; (4) worm populations decline, which reduces fish food and soil aeration; (5) algae blooms occur at first but later decline; (6) long-term detrimental effects on microbial populations are few; and (7) the pest-predator balance is disrupted, leading to pest resurgence and development of secondary pest problems. Insecticide effects on the rice arthropod community have been studied by Cohen et al (1994), Schoenly et al (1995), and Heong and Schoenly (1998). The effects of insecticides were shown to translate into ecological costs in the form of (1) food-chain-length reduction from about 3 to 2, making the sprayed fields more vulnerable to pest re-colonization; (2) disorganization of pest–natural enemy–other species relationships, and the food web structure as a whole; and (3) r-strategist[1] arthropods, such as planthoppers, were favored. When insecticide pressures decreased, arthropod biodiversity doubled and pest abundances declined (Heong et al 2007).

In addition to in-crop effects, a number of off-crop effects occur as vertebrates accumulate pesticide residues from drainage ditches and irrigation canals in fully irrigated (flooded) systems. Poorer farmers in many areas harvest snails, fish, crabs, and

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[1] The r-strategists are opportunists, selected for the characteristic of maximizing food intake, having high reproductive capacities, having high migratory abilities, and exploiting their ephemeral habitats. These species become pests when released from their natural biological controls (Southwood and Comins 1976).

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aquatic plants from these ditches and canals (Tejada and Magallona 1985). Groundwater contamination also occurs, resulting in well-water contamination (Bhuiyan and Castañeda 1995).

## Driving forces and alternatives for rice pest management

Major forces driving rice pesticide use, and rice pest management in general, include the development of alternative technologies, including the breeding of host-plant resistance among others; genetically modified (GM) rice varieties; rising labor costs, which affect herbicide use, rice policies, and prices; improved educational means of reaching growers with IPM messages at lower cost; pesticide prices; changes in pesticide regulations; and climate change. Labor costs continue to rise as incomes grow, and will continue to result in increased use of herbicides on rice in developing countries, especially in Asia, unless alternative weed management practices are developed and delivered. Herbicide use in Japan may decline due to a government policy to gradually reduce rice area. However, continued growth in demand for rice worldwide, especially in Asia, may exert upward pressure not only on rice prices but also on pesticide demand.

### Biotechnology

Biotechnology is just beginning to play a role in the development of alternatives to pesticide use and is likely to play a key role in the future. *Bt* rice has obtained biosafety certificates and is awaiting approval by the Ministry of Agriculture in China for stem borer control (Oryza 2010), and is also under development in other countries. Punjab Agricultural University in India is developing a *Bt* rice with resistance to leaffolders. Other GMOs have been developed and are awaiting regulatory or market approval.

Herbicide-tolerant Roundup Ready rice and Liberty Link rice have been available for some time, but have not been a high priority for release by the companies involved because of concerns over consumer acceptance. These varieties, if released in the U.S. and Japan, would result in a substitution among herbicides. However, in most developing countries, the varieties would likely increase herbicide use as a substitute for labor. Clearfield rice, a herbicide-resistant non-GM variety, has been released in the Americas, and applications for its approval have been made in Asia as well. Malaysia recently released Clearfield rice particularly to manage weedy-rice problems.

Although GMOs have potential to reduce pesticide use overall, most of them will not be released for several years because of regulatory delays and market concerns. For instance, *Bt* cotton has become widespread in the United States, China, and India, but approval for GM rice has been much slower. Being a food crop, rice has drawn more attention from groups opposed to transgenic crops. As a result, public agencies have been cautious both in research and in the regulatory process. Private companies have been cautious because of market concerns and because rice is mostly a self-pollinated crop, which makes it harder to manage the intellectual property. It is possible that the

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*Bt* rice in China, if approved for wide-scale production, will break the logjam on GM rice, if it proves to be profitable and reduces insecticides as promised. Evidence with data from experimental trials indicates that it will be so as a result of a large reduction in pesticide use in China even though the yield advantage may be small (Huang et al 2008, Wang et al 2010, Hui et al 2010). As noted above, some question how much *Bt* rice will reduce insecticide use in China unless there is a strong market campaign to change farmers' perceptions (Heong et al 2005, Cohen et al 2008).

Other pest-resistant rice varieties are under development through marker-assisted breeding (Jena and Mackill 2008). These varieties will not require stringent regulatory approval because they are not GMOs. The rice genome has been mapped for about 10 years now, and molecular-assisted breeding is being used at IRRI and in several national research systems to speed up the breeding for multiple pest resistance. The potential of resulting improved varieties to reduce pesticide use is significant if they are introduced with effective educational programs. We say improved and not new because the idea is to breed the resistance into mega-varieties that are already popular with farmers to help encourage widespread adoption. Varieties with resistance to bacterial leaf blight (BLB) that were developed using molecular markers are already available to farmers in Indonesia and China (Huang et al 2008).

In addition to host-plant resistance to diseases and animal pests, other methods can help reduce crop losses. The use of bio-pesticides, rotating rice with other crops, and altered planting dates are just a few. Simply improving crop health through proper fertility and water management can help as rice is a crop with a significant ability to compensate for injuries during the growing season if it is in an otherwise favorable production situation. Minimizing chemical use also helps to conserve beneficial insects, which can help keep insect pests in check. The growth of beneficial insect populations may also be stimulated by introducing nectar-rich flowers on the bunds and borders of rice areas (Gurr et al 2004, Gurr 2009). Promotion of IPM may overcome the effects of sales campaigns for pesticides, but, unfortunately, unless educational efforts are on a larger scale than at present across Asia and sustained, progress will be slow. Innovative efforts such as those by IRRI in Vietnam that use radio soap opera (Heong at al 2008) and multimedia campaigns (Escalada et al 1998, Heong et al 2008) to reach large numbers of growers will be required, in combination with continued improvement and enforcement of pesticide policies and regulations. If nonchemical alternatives can be found and disseminated in a sustainable manner, the long-run result will be a more sustainable rice culture.

Resistance problems can occur not only with pesticides but also with biotechnology solutions. To slow the development of pest resistance to biotech products on other crops, farmers have been asked to follow stewardship guidelines. For example, to preserve the efficacy of the "Clearfield" herbicide-resistance technology, rigorous guidelines are in place involving crop rotations, number of herbicide applications, and fallow management (BASF 2010). Likewise, farmers growing *Bt* corn in the United States are required to maintain a refuge around their corn fields to reduce the chances that insects that survive the *Bt* corn will breed with each other and produce resistant

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offspring. Many farmers do not follow these guidelines, however, and enforcing them is even more of a challenge in a developing country. For *Bt* rice, resistance management will require farmers to maintain a refuge as well. Because rice stem borers are monophagous, widespread planting of *Bt* rice may quickly lead to the development of resistance (Cohen et al 2008).

### Pesticide policies and regulations

A vast array of pesticide policies and regulations influence the use of pesticide and alternative pest management practices on rice. Although most developed countries such as the United States have more refined environmental regulations and food safety policies than do developing nations, most rice-producing countries have gradually tightened their pesticide rules in recent years. Twenty years ago, it was not uncommon to find no regulation of pesticides, regardless of toxicity. Today, most countries (at least nominally) abide by international standards for food safety developed by the CODEX Alimentarius Commission of FAO/WHO. That commission is an international body that sets guidelines on pesticide residue amounts that are considered in safety evaluations for approval of specific pesticides.

Most countries now use the WHO recommended classification of pesticide hazard in deciding how to classify and restrict specific chemicals. Individual products are classified in a series of tables, according to oral or dermal toxicity of the technical product, and its physical state (solid or liquid). Each product falls under one of four groups: (Ia) extremely hazardous, (Ib) highly hazardous, (II) moderately hazardous, and (III) slightly hazardous. Some major rice-producing countries have banned most Class Ia and Ib pesticides on rice even if they allow them for restricted use for other purposes. Pesticides such as monocrotophos, methyl-parathion, azinphosmethyl, and carbofuran are all Class I chemicals that were commonly used on rice (Heong and Escalada 1997b, Litsinger et al 2009) but have seen increased restrictions fairly recently. However, many of these chemicals still exist even in countries where they have been banned or otherwise restricted, and they find their way onto rice paddies. Even after regulations are in place, it can take years for enforcement to catch up with the millions of pesticide dealers and farmers who may be slow to abide by the regulations (see Box 1).

Almost every country producing rice has in place regulations that follow international guidelines and involve registration of pesticides only after field testing at multiple sites over at least 2 years. Data are provided on chemistry, toxicity, efficacy, and residues. However, key factors that continue to cause health and environmental issues are the continual use of nonregistered chemicals and the misuse (Tjornhom et al 1997) of all chemicals. For instance, Heong et al (1995a) found that, in the Philippines, more than 80% of farmers' insecticide sprays were deemed as misuse. Insufficient pesticide education is part of the problem, but incorrect information provided by local pesticide dealers is also a serious issue. In addition, many Asian countries do not regulate the use of multiple trade names for the same active ingredient. For example, in China, the same active ingredient is sold in some cases under more than 500 trade

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### Box 1. Pesticide policies in the Philippines

In the Philippines, a joint study led by IRRI and the University of the Philippines in Los Baños found that, in the late 1980s, farmers' health costs were greater than any economic benefits of the pesticides that at that time were being applied to rice (Jamora and Templeton 2008). In response, and in keeping with international protocols, the Fertilizer and Pesticide Authority (FPA) of the Philippines in the early to mid-1990s passed a new set of pesticide regulations that restricted the highly toxic chemicals commonly used on rice and encouraged safer pesticide practices. The use of all WHO Hazard Class I and some Hazard Class II pesticides was banned in 1994. However, enforcement and adoption of these regulations and practices took time. The importation and use of banned pesticides declined only gradually. A 2002 survey found that they were still heavily used (Palis et al 2006). However, a farmer survey in 2007 found that 93% of farmers said they no longer could find the banned chemicals in the marketplace and 90% said they no longer used them (Jamora and Templeton 2008). More than 99% of the pesticides actually applied were registered for use on rice in the Philippines. Of the registered chemicals used, 61% were Class II, 28% were Class III, and 11% were Class IV. The same survey found that safer pesticide practices were being followed than were found in a similar survey in 1991. Apparently, there has been some progress, albeit slow.

names. Because farmers purchase pesticides by trade names, they are often confused by them.

A number of other direct and indirect policies influence pesticides and pest management. First, countries have at various times directly subsidized pesticides to encourage their use. Those policies were found in the Philippines, Indonesia, Bangladesh, China, and many other countries, especially in the 1970s and '80s. For example, the Masagana 99 scheme in the Philippines subsidized pesticide use on rice from 1973 to 1986. Pesticide subsidies include not only subsidized pesticide prices but also the use of public extension services in promoting chemical use, as in China. In some cases, government-backed credit programs required the use of pesticides with the basic idea that they would reduce crop risk. Also, it is common for governments to maintain emergency budgets to purchase pesticides for free distribution when outbreaks occur or are reported (Farah 1993). Because of the time lag between the outbreak and release of funds, pesticides are often available to farmers only after the outbreak is over.

By the late 1980s, several countries began to rethink their pesticide subsidy policies. Health and environmental problems were becoming clearer, including the effects of chemicals on beneficial organisms. IPM programs were expanding in developed countries and beginning to draw attention in Asia as well. Pest resurgence was

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an increasing problem in rice as resistance built up to various chemicals. Economic difficulties in several countries also may have influenced them to reduce pesticide subsidies along with other public subsidies to agriculture. The removal of pesticide subsidies in Indonesia, for example, in the late 1980s is credited with reducing pesticide use in that country at the same time IPM programs were growing.

In some cases, pesticides were actually taxed through import tariffs on the technical (active ingredients) as well as the formulated product itself. The Philippines, for example, had a 10% tariff on the technical (active ingredient) product and a 3% tariff on formulated pesticides in the 1990s (Tjornhom et al 1998). These policies were altered in some countries as trade restrictions were modified following implementation of the Uruguay Round Trade Agreement. In some countries in Asia, exchange rates became overvalued in the 1990s and created an indirect subsidy to imports such as pesticides, and these indirect subsidies more than offset the tariffs (Tjornhom et al 1998). The Asian financial crisis squeezed out the overevaluation in most Asian countries, temporarily at least reducing those subsidies.

One factor that continues to strongly hinder adoption of bio-insecticides, bio-control agents, and pheromones as substitutes for synthetic chemicals in IPM programs, including rice IPM, is that they are often all treated in the same way as synthetic chemicals in the regulatory process. Pesticides are defined as any substance that is intended to prevent, destroy, attract, repel, or control a pest. Bio-pesticides or pheromones are considered pesticides even though they may be benign when it comes to effects on human health. As pesticides, they still must be examined and registered before their use is approved. Although everyone agrees with the need for registration, unless the registration process is streamlined for these substances that have consistently been found safe during testing elsewhere, their use may never spread. Many of these substances are locally produced biological products with local markets. Subjecting them to the complete review process is expensive. Chemical companies may fear their spread as they would reduce profits on sales of synthetic pesticides, and hence they have an interest in ensuring that bio-pesticides are slow to reach the market. The United States has streamlined the registration process for these types of products and other rice-producing countries should consider doing the same.

### Improving and integrating rice pest management practices

Better management of pesticides through IPM strategies began with combining pest-resistant varieties with insecticide application decisions based on decision thresholds (Litsinger et al 2009). Economic injury levels for rice pests were studied by IRRI and by many national institutions in the 1970s and ’80s (Dyck et al 1981, Litsinger et al 1987, Teng, 1994) and formed the basis for establishing decision thresholds for pesticide use. Spraying pesticides, in principle, involves complex reasoning (Zadoks 1985). Not only do thresholds themselves vary with stage of crop growth, level of injury, crop price, and other factors, but certain expensive chemicals are more economical than inexpensive ones when applied in the recommended amounts. Therefore, threshold analysis is of limited use on rice except to indicate when spraying is clearly useless.

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As discussed earlier, excessive and inappropriate use of pesticides can lead to the destruction of natural biological control services and to pest resurgence, secondary pest outbreaks, and the development of pesticide resistance (Heong 2009), but farmers have found it difficult to assess what, when, and how much to apply. Pesticide salesmen have influenced farmer decisions and the pesticide industry has lobbied governments to subsidize chemical use and relax pesticide regulations. Many farmers have been indoctrinated to the point that they are hesitant not to use pesticides (Matteson et al 1994). Problems with excessive pesticide use have gradually made some farmers more receptive to alternative IPM approaches, but IPM has often been pushed by scientists more than it has been demanded by farmers (Morse and Buhler 1997). In many cases, IPM scientists have not understood well enough the problems that farmers face and the wide influence of the chemical salesmen.

In an effort to overcome this disconnect between scientists and farmers, "farmer-first" approaches that were developed outside of IPM (Chambers et al 1989) were applied by IPM practitioners as well, first in farming systems research and extension and later in "farmer field schools" or FFS (Bartlett 2005). However, when the starting point was IPM, regardless of the approach, it still took scientists to lead, as farmers might have focused on other problems first if they had been given the choice. In many rice systems, farmers were more worried about constraints such as drought and floods than about pests.

The combination of excessive pesticide use, limited adoption of IPM by developing-country farmers, and the growth of farmer-first approaches led to the emergence of the FFS, first in Indonesia in the late 1980s, then elsewhere in Asia in the early 1990s, and later globally once it was institutionalized at FAO.[2] With FFS, instead of listening to talks or watching demonstrations, farmers observe, record, and discuss what is happening in their own fields from the time of planting until harvest. A typical FFS rice IPM program has 10–16 meetings, with about 25 farmers. The discovery and learning process is intended to provide an understanding of ecological concepts and their practical application. Since 1990, more than 2 million farmers have participated in farmer field schools in Asia alone (Bartlett 2005).

To some extent, the FFS approach to IPM diffusion has been controversial: it is strongly supported by some and disparaged by others. On the plus side, it has the advantage of involving high farmer participation, which makes it attractive not only to public institutions but also to grass-roots NGOs working in agriculture. It also has the advantage of having a well-defined set of steps that involve small group activities, making it possible to run a few or many FFSs depending on the budget. The hands-on involvement and intensity of the program help to reinforce its messages. It is one of the few approaches that help farmers understand the ecology of the system. On the negative side, the length and intensity of the program mean that it is costly per farmer reached compared with many other approaches—$25–50 per farmer participant is not uncommon (Ricker-Gilbert et al 2008). Therefore, given typical budgets for IPM diffusion, only a relatively small number of farmers can be reached. The hope has

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[2] Under the leadership of Peter Kenmore, who had initiated the Indonesia program.

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been that farmers who have been through an FFS program will train their neighbors. But, empirical studies have found little of this transfer of IPM knowledge (Feder et al 2004).

The assumption that farmers know a lot and that knowledge just has to be brought out of them is true but perhaps has been carried too far. The result is that farmers learn more about insects than they do about diseases because they can recognize insects more easily. Farmers know that they know a lot, but they also know that they do not know everything (Bentley 1989). Most farmers are receptive to at least trying new ideas when confronted with them, and will adopt them if they perceive the ideas make sense.

Partly because of the high cost of FFS and the slow spread of IPM messages, others working in rice IPM began experimenting with alternative approaches to disseminate IPM. Rather than trying to give complex messages to farmers, a few simple rules were developed by IRRI such as “Do not spray insecticides against leaf-feeding insects for the first 40 days of crop growth” (Heong et al 1998). IRRI had undertaken pest ecology studies and shown that the primary insect pests during the first 40 days are leaf-feeding insects, and that even high infestations could be tolerated by rice without significant yield loss (Heong 1990). Spraying insecticides for leaf-feeding insects in the first 40 days tends to remove beneficial predator insects, making the rice more susceptible to secondary pests such as brown planthoppers. Insecticides would then have to be sprayed again for the secondary pests.

Experiments were set up to test the efficacy of simple messages and they appeared to work well in the Philippines and Vietnam (Heong and Escalada 1997a, Heong et al 1995b). Farmers who received the messages reduced insecticide use by 50% after conducting an experiment to evaluate whether a simple rule of no spraying for 40 days after sowing (or 30 days after transplanting) would make a difference in their yields (Heong and Escalada 1997b). Simple messages are not a substitute for more in-depth farmer training, but can help in assuring that low-cost messages are received by large numbers of farmers to raise awareness and reduce pest problems and pesticide use.

More recently, the simple message concept was extended to the optimization of three critical inputs: seeds, fertilizer, and pesticides. IRRI and its partners implemented a program to stress three reductions of those inputs to (1) reduce the seeding rate with high-quality seeds and improved crop establishment, (2) optimize and thus prevent excessive N application through the use of a leaf color chart, and (3) reduce pesticide use through integrated pest management (Huan et al 2008). In Vietnam, the “Three Reductions, Three Gains” program used a radio drama, a television drama, a TV commercial, posters, flyers, and other extension efforts to promote the input reductions. This resulted in measured pesticide reductions of 13–33%, with higher yields and net incomes, and an improved environment (Huan et al 2008). But the results are variable, with Jamora and Templeton (2008) reporting only a modest gain.

Although IR8, the first high-yielding variety released with the Green Revolution in the late 1960s, was susceptible to many diseases and pests, varieties subsequently released had incorporated multiple resistance (Panda and Khush 1995). However, resistance is seldom complete and farmers were encouraged to continue to use pesti-

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cides for many years by pesticide dealers and others. Plant breeding efforts to build in further resistance have continued and modern varieties contain multiple genes for resistance in major rice-growing countries. IRRI has been instrumental in developing varieties with resistance to brown planthoppers, stem borers, green leafhoppers, tungro virus, blast, and bacterial blight. In fact, all IRRI-bred varieties are screened before release to ensure that they have at least a base level of resistance to these insects and diseases. More durable resistance is needed, and some progress has been made.

Breeding for pest resistance had become more efficient over time with the advent of new biotechnology tools. Despite the development of *Bt* rice with resistance to yellow stem borer in India, the Philippines, and China, no GM rice has been released commercially (although it appears that commercial release is close in China). However, marker-assisted selection (MAS) has been helpful for speeding up the breeding process for pest and nonpest traits. For example, IRRI developed lines with three bacterial blight resistance genes (*Xa4*, *Xa7*, and *Xa21*). As noted above, varieties developed through MAS for resistance to bacterial blight are currently available in Indonesia and China (Huang et al 2008).

MAS is particularly useful for developing tungo-resistant varieties due to the difficulty in screening for tungro resistance with conventional breeding (IRRI 2010). According to IRRI, progress has been made in defining the gene responsible for rice tungro spherical virus (RTSV) resistance. A gene (*Pi40*) with broad-spectrum resistance to multiple races of blast has also been identified through fine mapping. It is being incorporated in both indica and japonica breeding lines. A marker linked with brown planthopper resistance conferred by *Bph18* was MAS-validated in advanced backcross Japonica lines (IRRI 2009).

Weed control is another major concern and it has primarily been carried out through a combination of water management, hand weeding, and herbicides (Moody et al 1997, Labrada 2002). Few evidence-based agronomic recommendations and options are available to farmers to address emerging problems or reduce current weed losses. As a result, recent efforts have been undertaken to improve weed management and establish clear recommendations for farmers. “Palay Check” (or Rice Check”) is an example from the Philippines of an initiative to provide farmers with a complete set of recommendations, including integrating weed management into the recommended practices (PhilRice 2010). More commonly though, the most significant extension messages received by farmers are from herbicide suppliers and, with few exceptions, they emphasize herbicide use. In recent years, the development and release of herbicide-tolerant (HT) rice in the United States and Latin America has been a major innovation to overcome problems of weedy rice infestations. HT rice, however, has been accompanied by concerns over geneflow (e.g., Burgos et al 2008, Arroz 2009). Herbicide-tolerant rice is not yet available in Asia or Africa. In Asia, the availability of selective herbicides has become more widespread in addition to a wider range of products and formulations. Incidence of herbicide resistance in weeds is expected to “mirror” the situation that has occurred in other rice-growing areas, particularly in the Americas.

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## Future opportunities

### Weed management methods

Herbicides have long been the main weed management method for rice in Latin America and North America, and in countries such as Japan and the Republic of Korea, and they are an important intervention in other Asian countries as well such as Sri Lanka and Vietnam (Rao et al 2007). Although herbicides are valuable in many rice systems and essential in others, diversified approaches could take advantage of ecological processes such as crop suppression of weeds, promoting seed predation and decay, and suppressing emergence to elevate the effectiveness of weed management in the long term. In this way, herbicides could be seen as a component of an integrated approach, which could reduce herbicide applications, lessen the risk of resistance, and slow the change in weed composition. Integrated weed management approaches have been advocated by several authors (e.g., Liebman and Gallandt 1997).

Rice farmers in Asia usually implement integrated weed control measures such as soil cultivation, flooding, and hand weeding to reduce weed infestation. Flooding is the most important weed management practice in many rice systems, since it suppresses the emergence and growth of most weed species. Flooding after herbicide application or hand weeding can largely prevent subsequent weed growth and reduce the need for further interventions. Successful herbicide application in lowland direct-seeded rice is closely linked to water management to achieve selective control while minimizing phytotoxicity (Hill et al 2001). In the future, however, many farmers will have limited irrigation water, which will restrict their capacity to use flooding as a weed control measure (Tuong et al 2005). Nonetheless, with only shallow and intermittent flooding, the growth of many weeds can be greatly reduced (e.g., Chauhan and Johnson 2009b). Where farmers have limited irrigation water, early rather than later flooding would also make the best use of water to control weeds as once the canopy of the rice crop has closed, shading from the crop is likely to suppress weed growth. Despite the widespread use of water to control weeds, there are many gaps in our knowledge regarding the use of timing and depth of flooding as possible means to exploit differential tolerances between the crop and weeds.

Choice of tillage systems or crop establishment practices can change the "trajectories" of weed population shifts. For example, in the rice-wheat cropping system in India, a buildup of *Ischaemum rugosum* in wet-seeded rice may be discouraged by using no-till systems in either rice or wheat (Singh et al 2008). Likewise, repeated use of no-till in rice may lead to greater densities of *Echinochloa colona* (Chauhan and Johnson 2009a), which could then be discouraged by shifting back to wet-seeded rice (Singh et al 2008). Cropping practices causing less soil disturbance, such as no-till, concentrate weed seeds near the soil surface (Chauhan and Johnson 2010). In these situations, high germination rates for many weed species are expected if moisture conditions are adequate. Seeds at or near the soil surface are also more prone to predation and desiccation due to unfavorable weather conditions (Jacob Spafford et al 2006, Mohler and Galford 1997). Seed decay and predation reduce the seed bank and number of weeds germinating in the following season. No-till or delayed tillage,

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which prolong seed exposure to predators, could be incorporated into integrated weed management programs. Retaining crop residues as mulch on the soil surface has the potential to effectively suppress weeds. In addition to reducing seedling emergence, residues may also delay emergence and allow the crop to gain an advantage over weeds and reduce the need for control. Mulches, however, tend not to suppress weeds completely and therefore their use needs to be integrated with measures such as postemergence herbicides.

There are many gaps in our understanding of the factors influencing weed emergence and survival. Greater knowledge of the role these factors play in determining weed establishment and how they differ between species could greatly improve the effective application of current practices, and contribute to the development of novel weed management strategies.

### Insect management methods

Insect pest management in rice requires a broad ecological approach that includes biological, cultural, and occasionally chemical control combined with insect-resistant rice varieties (Heinrichs 2007). Naturally occurring biological control with indigenous predators, parasitoids, and insect pathogens is critical to rice insect management (Way and Heong 1994). These indigenous natural enemies have worked for thousands of years. They will be more important in the future than they have been in recent years, during which insecticides have often destroyed them. Unless destroyed by chemicals, predacious spiders are abundant in the field and attack all stages of rice insects. For example, the wolf spider, *Pardosa pseudoannulata*, is an important predator of brown planthopper, with one spider eating up to 45 hoppers per day (Heinrichs 2007). Because of the extensive use of insecticides, these spiders and numerous other predators and parasitoids have been suppressed and brown planthopper, a secondary pest, has become serious in many locations (Heong and Schoenly 1998, Heong 2009).

Numerous parasitoids attack the eggs, larvae, and pupae of the rice leaffolder. And, pathogens belonging to the fungi, bacteria, and virus groups play an important role in regulating rice insect pest populations (Heinrichs 2007). Many cultural practices can potentially control rice insect pests, such as (1) mixed cropping, (2) varying the age of seedlings at the time of transplanting, (3) water management, (4) fertilizer management, (5) crop rotation, (6) the number of rice crops per year, (7) planting time, (8) trap crops, (9) tillage practices, (10) weeding, and (11) synchronous planting, among others (Heinrichs 2007). Chemical use should be contemplated only when an insect pest is proven to cause loss (Way and Heong 1994).

IRRI is attempting to develop ecological engineering methods to strengthen natural enemy biodiversity that are fundamental to increasing biological-control ecosystem services to regulate pests. The prospect of using ecological engineering in rice was discussed by Gurr (2009). This work is being undertaken in China, Thailand, Malaysia, and Vietnam using methods such as increasing beneficial plants along bunds to provide food sources for the natural enemies and improving timing of sowing to avoid invasion of pest vectors carrying virus diseases (IRRI 2009). Plants under attack

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by pests often produce volatile chemicals that attract natural enemies (Bruce and Pickett 2007). These herbivore-induced plant volatiles (HIPVs) have been synthesized and used as sprays to obtain elevated biological control activities, suggesting that HIPVs can be used to attract natural enemies to crops (Gurr 2009). Lu et al (2006) found that rice plants attacked by the brown planthopper attracted more egg parasitoids.

As discussed above, there is potential as well to achieve varietal resistance to insects through biotechnology. *Bt* rice for stem borer control is one example, but there are others as well. The use of MAS for speeding up the development of varieties, such as ones with resistance to brown planthopper, is another example. MAS may be a more important solution to speeding up the development of varietal resistance than GMOs, at least until the regulatory and market constraints for the latter are resolved. Climate change may increase the demand for water-conserving varieties, and also for varieties with improved insect tolerance as ecosystems evolve with global warming.

In the foreseeable future, insecticides will remain the dominant tools farmers use in their fields. It is risky and expensive, costing $256 million, to research, develop, and register a new crop protection product, and only 1 in 139,000 chemicals make it from the laboratory to the field (Croplife America 2010). Chemical companies are likely to focus on developing new chemicals with novel properties, such as buprofezin and the neonicotinoids, selective modes of action (Ishaaya et al 2007), and new delivery systems, such as nano encapsulation of imidacloprid (Guan et al 2008). However, their proper and sustainable use in rice fields will depend on farmers' knowledge, equipment, access to the novel technologies and well-balanced advice, good product stewardship programs, and well-managed regulatory and marketing structures. Rice planthoppers have developed multiple layers of resistance to the neonicotinoids introduced in some countries about 10 years ago because of excessive use (Matsumura et al 2009). Buprofezin, a product noted for its selectivity to planthoppers, is often not available or not recommended to farmers by rural pesticide dealers because of its higher cost and delayed mortality effects. Some companies institute good stewardship programs to ensure safe and proper use of pesticides, but others do not, and they exploit the market and prey on farmers' lack of knowledge, thus exacerbating pesticide misuse.

### Disease management practices

Successful rice disease management begins with varietal resistance as a base because it is the simplest and cheapest way for farmers to manage disease. For many diseases, once an epidemic develops in a rice crop, the spatial-temporal pattern of epidemics (many fungi and bacteria, most viruses) and the injury-crop loss relationships (Savary et al 2006a) may easily lead to difficult management. Resistances to diseases can, in several diseases, be overcome by pathogens, and so new resistances are needed every few years. In addition, if environmental conditions are highly favorable for a disease such as blast, or if new pathogen races occur, epidemics can be triggered on previously resistant varieties (Teng 1994, Leung et al 2003, Wopereis et al 2009). Therefore, other control methods can be combined with varietal resistance, including (1) choose crop establishment dates that do not coincide with environmental conditions that are

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conducive to disease intensification, (2) synchronize sowing or transplanting to prevent green bridges that favor disease transmission across crops, (3) use healthy or treated seed, (4) reduce the sources of primary inoculum, (5) use proper plant nutrition, and (6) use genetic diversity through varietal rotation, varietal mixtures, intercropping, and crop rotation (Zadoks and Schein 1979, Teng 1994, Croplife Asia 2004).

Because of the fundamental importance of varietal resistance to disease management in rice, disease control is a strong target for molecular techniques. The use of MAS for speeding up the development of varieties with resistance to bacterial blight, tungro, and blast is an excellent example (Jena and Mackill 2008).

Preventive or curative chemical use is usually not desirable. Unfortunately, for some diseases for which (1) no effective resistance exists and (2) epidemics are relatively slow and strongly aggregated, fungicides combined with crop management may offer efficient options. Seed health management—the securing and processing of seed lots that are specifically harvested and stored for crop establishment—is a key element to prevent seed-borne diseases (Mew 1991).

### Rodent pest management

In the 1960s, a wide range of chemical rodenticides became available on the global market. However, despite the development of a new generation of chemicals in the 1980s, rodents developed tolerance of most of them. There are also serious concerns over their humaneness, and their impact on nontarget species. Ecologically based rodent management, or EBRM (Singleton 1997), has now taken center stage for rodent control in Asia, Australia, and eastern Africa (Stenseth et al 2003, Singleton et al 2007). In Southeast Asia, EBRM has been particularly effective in intensive lowland rice agroecosystems, leading to acceptance of EBRM by smallholder farmers (Singleton et al 2005).

### IPM delivery approaches

The fundamental question for the future of rice pest management is how to achieve widespread use of IPM alternatives to manage rice pests with minimal use of pesticides, minimum externality costs, high yield, and high profitablity. Many scientists argue that IPM practices are currently available to manage most important rice pests in an economically viable manner with few if any pesticides, although improved IPM practices are continually needed given (1) the dynamic nature of pest populations, (2) increasing labor costs, and (3) new and aggressive marketing strategies of the pesticide industry. Unfortunately, the efficacy of rice IPM is currently hindered by the excessive use of chemicals that destroy ecosystem services that regulate pests, and approaches used to encourage reducing unnecessary pesticide use have not resulted in widespread farmer adoption of IPM. The question is how to achieve that adoption.

Some aspects of pest management, such as weed management in direct-seeded rice, are “knowledge-intensive,” and as such improving the availability of information is a prerequisite for sustainable weed management (Rao et al 2007). Changes in weed flora are likely and the provision of relevant information to support decision making is

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essential for appropriate management responses. Such information, however, is often not available to farmers.

Some argue that adoption of IPM is already widespread because most farmers currently plant improved rice varieties with at least some pest resistance and many farmers also hand-weed. However, most definitions of IPM include not only the use of multiple types of pest management practices, but also synthetic chemicals are used only when essential. Therefore, most would say that the majority of farmers currently apply too many insecticides and fungicides to fit the definition of their having adopted IPM. Pest-resistant varieties are clearly not fully appreciated by farmers, as pesticides are still being used to treat the same pests for which the varieties are said to be resistant.

If IPM is indeed more economically profitable with lower pesticide use, then one must ask why pesticides are still the preferred option for most rice farmers. One answer is that adoption of any pest management practice depends on farmers (1) being aware of its existence, (2) perceiving that it will benefit them if it is adopted, and (3) finding it available and understanding how to use it. Pesticides meet all three requirements. Most pest-resistant varieties do as well up to a point. However, many types of cultural and biological controls for pests fall short on the second and especially the third requirement. They are information-intensive, and in some cases even require coordination among farmers in an area. Therefore, IPM information must reach farmers though intensive delivery approaches such as FFS or the information must be simplified to facilitate its understanding by farmers.

Several other factors hinder IPM diffusion. First, governments often find ways to directly or indirectly subsidize pesticides and create roadblocks to the approval of nonchemical practices. Second, many IPM practices that scientists or even farmers develop address only one specific pest at a time. Therefore, farmers may apply chemicals for others pests, thereby defeating the efficacy of the first practice or facilitating secondary pest outbreaks. Now, let's take a look at how each of these problems can be overcome.

The issue of governments subsidizing pesticides requires a concerted effort to educate and modify the attitudes of plant protection officials and policymakers who decide about pesticide policies and regulations, the problems associated with pesticide use, and the benefits of IPM (Heong 2009). Plant protection officials, public extension agents, and even credit officers are often placed in situations where they understand the problems of farmers using pesticides, but they must follow the rules and regulations favoring chemical use that were established by higher-level policymakers. They tend to use procedural or political reasoning in their decision making. Examples of policies or rules that require chemical use are the government distribution of free or subsidized pesticides during a pest outbreak, or a requirement for farmers to have pesticide plans to obtain credit. An example of a policy roadblock to nonchemical use is a requirement for long and expensive testing for a biological control product to be approved for release or import even if that product was already found safe in countries with extensive testing procedures. This is especially important to prevent extension staff from becoming formal or informal sales persons for pesticides (Matteson 2000).

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In some cases, scientists from the public sector also serve as consultants to pesticide companies, creating a potential conflict of interest.

The issue of farmers attempting to adopt one or a few IPM practices while still applying chemicals for most of their other pest problems is a concern. This would seem to argue for the widespread use of FFS, but public budgets are insufficient to reach very many farmers with such an expensive approach. The existing estimates of 2–3 million farmers having been reached with FFS after two decades means that only a tiny fraction of producers have been reached. In addition, the turnover of farmers and discontinuance may erode the effects (Escalada et al 2009). The simple rule or heuristic approach such as “Do not spray rice for the first 40 days” reached more farmers and reduced chemical use to a greater extent (Heong et al 1998), but was not comprehensive enough to cover all aspects. The follow-up campaign of “Three Reductions, Three Gains” was a stronger step in the right direction (Huan et al 2008). Although it may not be as information-intensive as FFS, it integrates the messages of the importance of appropriate plant fertilization, fewer but higher quality seeds, and reducing the use of pesticides. Importantly, the three reduction message could be spread through a variety of mass media, including radio soap opera, to reach more farmers (Heong et al 2008).

The media approach alone, however, is not sufficient to communicate all important messages to farmers, especially if a message is complex and if there are problems that farmers may not recognize. And, the knowledge and ideas that farmers have will not be built upon. That problem could be addressed through integrated IPM research and delivery programs that include demonstration sites that are strategically placed and linked to research and extension. Sites for FFS programs could coincide with some of these demo sites, although the sites would function for a longer period of time than an FFS course. At the demo sites, farmers would be integrally involved with the scientists in testing IPM practices, providing feedback, and experimenting on their own.

Active research is needed in each rice-growing country on the most effective mass media approaches. Although some basic approaches such as radio messages, posters, and leaflets are suitable at most sites, others such as TV dramas and plays may work only in specific areas. Modern communication technology is evolving rapidly and is likely to present new mass media opportunities. An important aspect of using mass media is to figure out how to simplify an integrated set of practices into a message that still has enough information content. To the extent that various delivery mechanisms can transmit information repeatedly on similar packages through different but complementary means would improve the chances of widespread and sustainable success.

One of the reasons that pesticides have been so popular is that the private sector can make a profit off of them and therefore it has an incentive to market them. To the extent that some of the components of IPM packages can be distributed (sold) through small or large private entities, the chances of widespread distribution would increase as well. In some cases, it may be possible to use the pesticide company tactics and allow scientists or even extension workers to receive commissions for their involvement

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with private entities. In addition, IPM researchers and practitioners need to learn about marketing principles and develop more appealing ways to extend (or sell) IPM.

IPM in schools is another complementary but underused delivery strategy. By preparing IPM educational materials that can be used in schools, the awareness and perception requirements mentioned above can be met at a modest cost on a widespread basis. Teaching children about ecological principles before they are tempted to use pesticides would help even the playing field. One of the keys to implementing a school IPM program is to work to have it mandated from the top of the educational system. A good example is provided by the Pennsylvania School IPM program in the United States (Pennsylvania State University 2009).

### Ecosystem approaches

Despite ecology having increasingly been emphasized since the 1960s, the concepts of "ecosystem" and "ecosystem management" approaches to IPM are yet to be truly implemented (Maltby et al 1999). Awareness has been growing, however, of the importance of "ecosystem services" to human welfare and that the world's poor have a disproportionate, direct reliance on these ecosystem services (MEA 2005). In maintaining ecosystem services, biological interactions are important (e.g., the relation of predators and prey), and biodiversity has an important role in regulating ecosystem services, such as pest and disease regulation and pollination (UNEP-WCMC 2007). Biodiversity describes the abundance and diversity of genes and species, ecosystems, and habitats within a region and, in the context of pest buildup, the roles of many species in the landscape are poorly understood. Such interactions have been recognized, for example, in the relations between natural enemies and the dynamics of insect pests in rice, but they have not been broadly applied to other pests. Studies have been undertaken to record the response of weed flora to crop management (e.g., Man and Mortimer 2002, Singh et al 2008) and to determine the factors that influence establishment and growth (e.g., Chauhan and Johnson 2009b). Such studies, however, involve very few species and do not consider how changes in one population may affect another. More understanding of interactions within the ecosystem is needed to be able to anticipate undesirable changes. Further, greater research efforts are required to provide more precision in predicting undesirable changes in weed flora, and in how to address these changes with appropriate management practices and decision tools.

## Summary and conclusions

Rice pest problems are serious but, ironically, at least for insects, have been worsened by many of the pesticide applications designed to address them. Recent BPH outbreaks in China, India, and Thailand are examples of secondary pest problems that have become primary pest problems as a result of excessive chemical use. Such insect outbreaks have also caused viral epidemics, with serious consequences. As labor costs continue to rise, especially in Asia, where 90% of all rice is produced, herbicide use is also expected to increase unless new improved alternatives for weed control are developed and adopted. The misuse of pesticides has resulted in acute and chronic

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health problems with eyes, skin, and respiratory, cardiovascular, and neurological systems. Pesticide use has affected the number of species in rice paddies, relative composition of species, and residue accumulation in surviving populations. Several off-paddy effects occur as vertebrates accumulate pesticide residues.

Pesticide use on rice has leveled off in recent years, and the change in types of active ingredients applied toward ingredients that are more environmentally benign represents progress. Given the cost of registering new chemicals today, it is possible that the tide will swing more toward other IPM practices in the future. For many diseases, host-plant resistance represents the cornerstone of IPM, and maintenance breeding, enabling rotation of new resistance genes, is a critical element for the future. Marker-assisted breeding—and its widespread use in rice-producing countries—represents a key advance and should reduce costs in this area. However, forces are also at work that may hamper IPM implementation and increase pesticide use in the future without solving pest problems. Unless there is sufficient research on IPM alternatives, improved IPM delivery methods designed to achieve widespread IPM dissemination, continued tightening of pesticide regulations and enforcement, and improved policies, these forces may prevail.

Pesticide data trends indicate a long way to go to achieve widespread adoption of ecologically sound pest management. Some progress has been made, but more and faster changes are essential for sustainable rice production systems. A concerted effort is needed that focuses on policy, research, training, and communication approaches. The following actions constitute important elements of this concerted effort:

1. Enlightened pest management policies and regulations are needed. These can be facilitated by programs and processes that engage policymakers in dialogue to modify their perceptions. All subsidies for synthetic pesticides should be abolished and registration processes for bio-pesticides and pheromones should be simplified. Crop insurance mechanisms should be encouraged where practical as one problem is that farmers apply pesticides as “insurance” against crop losses.
2. Research support is needed for a wide range of IPM components that include host-plant resistance as well as cultural and biological control methods. Biotechnology opportunities for developing host-plant resistance to pests should be explored as well and scientifically based regulatory processes refined. Fortunately, significant research efforts are under way to develop and refine IPM component technologies. The key will be to have a complementary set of cost-effective delivery approaches that can be implemented in a widespread area.
3. IPM research and delivery methods must rely on a combination of approaches that include (a) mass media transmittal of simple messages that focus on practice clusters such as the “three reductions” message, (b) on-farm research that links farmers and extension workers to researchers, (c) substantial private-sector involvement, and (d) IPM in schools.
4. Pesticides are likely to remain important tools in rice pest management for many years, but an integrated approach is needed that can reduce reliance on

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pesticide applications, lessen the risk of resistance, and slow the change in pest composition. To the extent that pesticides are part of the IPM toolbox for pests, the focus should be on new-generation selective, low-toxicity pesticides, biopesticides, and improved application technologies.

## References

Antle J, Pingali PL. 1994. Pesticides, productivity, and farmer health: a Philippine case study. Am. J. Agric. Econ. 73(3):418-430.

Arroz. 2009. Here’s the dilemma. In: Brazilian rice yearbook. Santa Cruz do Sul: Editora Gazeta. p 75-93.

Bartlett A. 2005. Farmer field schools to promote integrated pest management in Asia: the FAO experience. Paper presented at the Workshop on Scaling Up Case Studies in Agriculture, International Rice Research Institute, Bangkok, Thailand. 16-18 August 2005.

BASF. 2009. Clearfield rice stewardship recommendations—2009. www.agproducts.basf.us/edu/clearfield, accessed 5 January 2010.

Bentley J. 1989. What farmers don’t know can’t help them: the strengths and weaknesses of indigenous knowledge in Honduras. Agric. Human Values 6:25-31.

Bhuiyan SI, Casteñeda AR. 1995. The impact of ricefield pesticides on the quality of freshwater resources. In: Pingali PL, Roger PA, editors. Impact of pesticides on farmer health and the rice environment. Norwell, Mass. (USA) and Los Baños (Philippines): Kluwer Academic Publishers and the International Rice Research Institute.

Bonman JM, Khush GS, Nelson RJ. 1992. Breeding for resistance to pests. Annu. Rev. Phytopathol. 30:507-528.

Bruce TJA, Pickett JA. 2007. Plant defence signaling induced by biotic attacks. Curr. Opin. Plant Biol. 10:387-392.

Burgos NR, Norsworthy JK, Scott RC, Smith KL. 2008. Red rice (*Oryza sativa*) status after 5 years of imidazolinone-resistant technology in Arkansas. Weed Technol. 22:200-208.

Chauhan BS, Johnson DE. 2009a. Influence of tillage systems on weed seedling emergence pattern in rainfed rice. Soil Tillage Res. 106:15-21.

Chauhan BS, Johnson DE. 2009b. Ecological studies on *Cyperus difformis, C. iria* and *Fimbristylis miliacea*: three troublesome annual sedge weeds of rice. Ann. Appl. Biol. 155:103-112.

Chauhan BS, Johnson DE. 2010. The role of seed ecology in improving weed management strategies in the tropics. Adv. Agron. 105:221-262.

Chambers R, Pacey A, Thrupp LA. 1989. Farmer first: farmer innovation and agricultural research. London (UK): Intermediate Technology Publications.

Cheng JA. 2009. Rice planthopper problems and relevant causes in China. In: Heong KL, Hardy B, editors. Planthoppers: new threats to the sustainability of intensive rice production systems in Asia. Los Baños (Philippines): International Rice Research Institute. p 157-178.

Chiarappa L, editor. 1971. Crop loss assessment methods. FAO Manual on Evaluation and Prevention of Losses by Pests, Diseases, and Weeds. Farnham (England): Commonwealth Agricultural Bureaux.

Cohen M, Chen M, Bentur JS, Heong KL, Ye G. 2008. Bt rice in Asia: potential benefits, impact, and sustainability. In: Romels J, Shelton A, Kennedy G, editors. Integration of insect-resistant GM crops within IPM programs. Springer.

2010. Pp 297 - 332. Ch 2.5. In " Rice in the global economy: strategic research and policy issues for food security. (eds) S. Pandey, D Byerlee, D Dawe, A Dobermann, S. Mohanty, S. Rozelle, and B. Hardy. Los Banos; Philippines. International Rice Research Institute. 477 p.

Cohen MB, Savary S, Huang N, Azzam O, Datta SK. 1998. Importance of rice pests and challenges to their management. In: Dowling NG, Greenfield SM, Fischer KS, editors. Sustainability of rice in the global food system. Pacific Basin Study Center, UC Davis and IRRI, Los Baños. p 145-164.

Cohen JE, Schoenly K, Heong KL, Justo H, Arida G, Barrion AT, Litsinger JA. 1994. A food web approach to evaluating the effect of insecticide spraying on insect pest population dynamics in a Philippine irrigated rice ecosystem. J. Appl. Ecol. 31:747-763.

Croplife Asia. 2004. Rice IPM Module 4, Aglearn.net, www.aglearn.net/riceIPMModule4.html, accessed 20 December 2009.

Croplife America. 2010. Crop protection facts and pesticide data. www.croplifeamerica.org/crop-protection/pesticide-facts, accessed July 2010.

Dasgupta S, Meisner C, Wheeler D. 2006. Is environmentally friendly agriculture less profitable for farmers? Evidence on integrated pest management in Bangladesh. Rev. Agric. Econ. 29(1):103-118.

Dawe D. 2002. The 2nd Green Revolution. Rice Today 1(1):30.

Devi PI. 2007. Pesticide use in the rice bowl of Kerala: health costs and policy options. South Asia Network for Development and Environmental Economics (SANDEE) Working Paper No. 20-07. Kathmandu, Nepal.

Dyck VA, Than Hun Dulay AC, Salinas Jr GD, Orlido GC. 1981. Economic injury levels for rice insect pests. Agric. Res. J. Kerala 19:75-85.

Escalada MM, Heong KL, Huan NH, Mai V. 1999. Communications and behavior change in rice farmers' pest management: the case of using mass media in Vietnam. J. Appl. Comm. 83:7-26.

Escalada MM, Heong KL, Huan NH, Chien HV. 2009. Changes in rice farmers' pest management beliefs and practices in Vietnam: an analytical review of survey data from 1992 to 2007. In: Heong KL, Hardy B, editors. Planthoppers: new threats to the sustainability of intensive rice production systems in Asia. Los Baños (Philippines): International Rice Research Institute. p 447-456.

Farah J. 1993. Pesticide policies in developing countries: Do they encourage excessive pesticide use? World Bank Discussion Paper 238. Washington, D.C. (USA): World Bank.

Feder G, Murgai R, Quizon JB. 2004. Sending farmers back to school: the impact of farmer field schools in Indonesia. Rev. Agric. Econ. 26:45-62.

Gallagher KD, Kenmore PE, Sogawa K. 1994. Judicial use of insecticides deter planthopper outbreaks and extend the role of resistant varieties in Southeast Asian rice. In: Denno RF, Perfect TJ, editors. Planthoppers, their ecology and management. London (UK): Chapman and Hall. p 599-614.

Graf B, Lamb R, Heong KL, Fabellar LT. 1992. A simulation model for the population dynamics of the rice leaffolders (Lepidoptera: Pyralidae) and their interactions with rice. J. Appl. Ecol. 29:558-570.

Guan H, Chi D, Yua J, Lia X. 2008. A novel photodegradable insecticide: preparation, characterization and properties evaluation of nano-imidacloprid. Pest. Biochem. Physiol. 92:83-91.

Gurr GM. 2009. Prospects for ecological engineering for planthoppers and other arthropod pests in rice. In: Heong KL, Hardy B, editors. Planthoppers: new threats to the sustainability of intensive rice production systems in Asia. Los Baños (Philippines): International Rice Research Institute. p 371-388.

2010. Pp 297 - 332. Ch 2.5. In " Rice in the global economy: strategic research and policy issues for food security. (eds) S. Pandey, D Byerlee, D Dawe, A Dobermann, S. Mohanty, S. Rozelle, and B. Hardy. Los Banos; Philippines. International Rice Research Institute. 477 p.

Gurr GM, Wratten SD, Altieri MA, editors. 2004. Ecological engineering for pest management. Collingwood (Australia): CSIRO Publishing.

Heinrichs EA. 2007. Management of rice insect pests. Radcliffe's IPM World Textbook. St. Paul, Minn. (USA): University of Minnesota. http://ipmworld.umn.edu/chapters/heinrich.htm, accessed 20 December 2009.

Heong KL. 1990. Feeding rates of the rice leaffolder, *Chaphalocrosis medicinalis* Lepidoptera: Pyralidae, on different plant stages. J. Agric. Entomol. 7:81-90.

Heong KL, Escalada MM, Huan NH, Mai V. 1998. Use of communication media in changing rice farmers' pest management in South Vietnam. Crop Prot. 17(5):413-425.

Heong KL. 1996. Pest management in tropical rice ecosystems: new paradigms for research. In: Hokyo N, Norton GA, editors. Proceedings of the International Workshop on Pest Management Strategies in Asian Monsoon Agroecosystems. Kyushu National Agricultural Experiment Station, Ministry of Agriculture, Forestry and Fisheries, Japan. p 139-154.

Heong KL, et al. 2005. Letter to *Science*: debate over a GM rice trial in China. Science 310:231.

Heong KL, Manza A, Catindig J, Villareal S, Jacobsen T. 2007. Changes in pesticide use and arthropod biodiversity in the IRRI research farm. Outlooks Pest Manage.

Heong KL. 2009. Are planthopper problems caused by a breakdown in ecosystem services? In: Heong KL, Hardy B, editors. Planthoppers: new threats to the sustainability of intensive rice production systems in Asia. Los Baños (Philippines): International Rice Research Institute. p 221-232.

Heong KL. 2009. http://ricehoppers.net, accessed 31 December 2009.

Heong KL, Escalada MM. 1997a. Perception change in rice pest management: a case study of farmers' evaluation of conflict information. J. Appl. Comm. 81(2):3-17.

Heong KL, Escalada MM. 1997b. A comparative analysis of pest management practices of rice farmers in Asia. In: Heong KL, Escalada MM, editors. Pest management of rice farmers in Asia. Los Baños (Philippines): International Rice Research Institute. p 227-245.

Heong KL, Escalada MM, Huan NH, Ky VH, Thiet LV, Chien HV. 2008. Entertainment-education and rice pest management: a radio soap opera in Vietnam. Crop Prot. 27:1392-1397.

Heong KL, Escalada MM, Lazaro AA. 1995a. Misuse of pesticides among rice farmers in Leyte, Philippines. In: Pingali PL, Roger PA, editors. Impact of pesticides on farmers' health and the rice environment. San Fancisco, Calif. (USA): Kluwer Press. p 97-108.

Heong KL, Schoenly KG. 1998. Impact of insecticides on herbivore-natural enemy communities in tropical rice ecosystems. In: Haskell PT, McEwen P, editors. Ecotoxicology: pesticides and beneficial organisms. London (UK): Chapman and Hall. p 381-403.

Heong KL, Teng PS, Moody K. 1995b. Managing rice pests with less chemicals. GeoJournal 35:337-349.

Hill JE, Mortimer AM, Namuco OS, Janiya JD. 2001. Water and weed management in direct-seeded rice: Are we headed in the right direction? In: Peng S, Hardy B, editors. Rice research for food security and poverty alleviation. Los Baños (Philippines): International Rice Research Institute. p 491-510.

Huan NH, Chien HV, Quynh PV, Tan PS, Du PV, Escalada MM, Heong KL. 2008. Motivating rice farmers in the Mekong Delta to modify pest management and related practices through mass media. J. Int. Pest Manage. 54:339-346.

Huang J, Hu R, Rozelle S, Pray C. 2008. Genetically modified rice, yields, and pesticides: assessing farm-level productivity effects in China. Econ. Dev. Cult. Change 56(2):241-263.

2010. Pp 297 - 332. Ch 2.5. In " Rice in the global economy: strategic research and policy issues for food security. (eds) S. Pandey, D Byerlee, D Dawe, A Dobermann, S. Mohanty, S. Rozelle, and B. Hardy. Los Banos; Philippines. International Rice Research Institute. 477 p.

Huang J, Qiao F, Zhang L, Rozelle S. 2003. Farm pesticide, rice production, and human health. E&E Research Reports. www.eepsea.org/uploads/user-S/10536115330ACF268.pdf.

Hui X, Chen L, Wang F, Lu B. 2010. Yield benefit and underlying cost of insect-resistance transgenic rice: implication in breeding and deploying transgenic crops. Field Crops Res. 118:215-220.

IRRI (International Rice Research Institute). 2009. Web site. http://beta.irri.org/index.php/Home/Welcome/Frontpage.html.

IRRI (International Rice Research Institute). 2010. Web site. http://beta.irri.org/news/images/stories/ricetoday/9-1/News.pdf.

Ishaaya I, Barazani A, Konsedalov S, Horowitz AR. 2007. Insecticides with novel modes of action: mechanism, selectivity and cross-resistance. Entomol. Res. 37:148-152.

Jacob Spafford H, Minkey DM, Gallagher RS, Borger CP. 2006. Variation in post dispersal weed seed predation in a crop field. Weed Sci. 54:148-155.

Jamora N, Templeton D. 2008. The power of policy. Rice Today 7(2):44-45.

Jena KK, Mackill DJ. 2008. Molecular markers and their use in marker-assisted selection in rice. Crop Sci. 48:1266-1276.

Kishi M, Hirschhorn N, Qjajadisastra M, Satterlee LN, Strowman S, Dilts R. 1995. Relationship of pesticide spraying to signs and symptoms in Indonesian farmers. Scand. J. Work Environ. Health 21:124-133.

Labrada R. 2002. The need for improved weed management in rice. Proceedings of the 20th Session of the International Rice Commission, Bangkok, Thailand, 23-26 July 2002.

Leung H, Zhu Y, Revilla-Molina I, Fan JX, Chen H, Pangga I, Vera Cruz C, Mew TW. 2003. Using genetic diversity to achieve sustainable rice disease management. Plant Dis. 87:1156-1169.

Liebman M, Gallandt ER. 1997. Many little hammers: ecological management of crop-weed interactions. In: Jackson LE, editor. Ecology in agriculture. London (UK): Academic Press. p 291-346.

Litsinger JA, Canapi BL, Bandong JP, de la Cruz CG, Apostol RF, Pantua PC, Lumaban MD, Aviola III AL, Raymoundo F, Libertario EM, Loevinsohn ME, Joshi RC. 1987. Rice crop loss from insect pests in wetland and dryland environments of Asia with emphasis on the Philippines. Insect Sci. Appl. 8:677-692.

Litsinger JA, Libertario EM, Canapi BL. Eliciting farmer knowledge, attitudes, and practices in the development of integrated pest management programs for rice in Asia. In: Peshin R, Dhawan AK, editors. Integrated pest management: dissemination and impact. Volume 2. New York (USA): Springer.

Lu Y, Wang X, Lou Y, Cheng J. 2006. Role of ethylene signaling in the production of rice volatiles induced by the rice brown planthopper, *Nilaparvata lugens*. Chinese Sci. Bull. 51:2457-2465.

Maltby E, Holdgate M, Acreman MC, Weir A. 1999. Ecosystem management: questions for science and society. Royal Holloway Institute for Environmental Research, Royal Holloway, University of London, Egham, UK.

Man A, Mortimer M. 2002. Weed species shifts in response to herbicide applications in wet seeded rice in Malaysia. In: Pandey S, Mortimer M, Wade L, Tuong TP, Lopez K, Hardy B, editors. Direct seeding: research strategies and opportunities. Los Baños (Philippines): International Rice Research Institute. p 357-368.

Matsumura M, Takeuchi H, Satoh M, Sanada-Morimura S, Otuka A, Watanabe T, Thanh DV. 2009. Current status of insecticide resistance in rice planthoppers in Asia. In: Heong

2010. Pp 297 - 332. Ch 2.5. In " Rice in the global economy: strategic research and policy issues for food security. (eds) S. Pandey, D Byerlee, D Dawe, A Dobermann, S. Mohanty, S. Rozelle, and B. Hardy. Los Banos; Philippines. International Rice Research Institute. 477 p.

KL, Hardy B, editors. Planthoppers: new threats to the sustainability of intensive rice production systems in Asia. Los Baños (Philippines): International Rice Research Institute. p 233-243.

Matteson PC. 2000. Insect pest management in tropical irrigated rice. Annu. Rev. Entomol. 45:549-574.

Matteson PC, Gallagher KD, Kenmore PE. 1994. Extension of integrated pest management for planthoppers in Asian irrigated rice: empowering the user. In: Denno RF, Perfect TJ, editors. Planthoppers: their ecological management. New York (USA): Chapman and Hall. p 656-685.

MEA (Millennium Ecosystem Assessment). 2005. Ecosystems and human well-being: synthesis. Washington, D.C. (USA): Island Press. www.millenniumassessment.org/en/synthesis.aspx.

Meerburg BG, Singleton GR, Leirs H. 2009. The year of the rat ends – time to fight hunger! Pest Anim. Sci. 65:351-352. DOI 10.1002/ps.1718.

Mew TW. 1991. Disease management in rice. In: CRC handbook of pest management in agriculture. 2nd Edition, Vol. III. Boca Raton, Fla. (USA): CRC Press. p 279-299.

Mohler CL, Galford AE. 1997. Weed seedling emergence and seed survival: separating the effects of seed position and soil modification by tillage. Weed Res. 37:147-155.

Moody K. 1991. Weed management in rice. In: CRC handbook of pest management in agriculture. 2nd Edition, Vol. III. Boca Raton, Fla. (USA): CRC Press. p 301-338.

Moody K, Escalada MM, Heong KL. 1997. Weed pest management practices of rice farmers in IIoilo, Philippines. In: Heong KL, Escalada MM, editors. Pest management of rice farmers in Asia. Los Baños (Philippines): International Rice Research Institute. p 143-160.

Morse S, Buhler W. 1997. IPM in developing countries: the danger of an ideal. Integr. Pest Manage. Rev. 2:175-185.

Naylor R. 1996. Herbicides in Asian rice production. In: Naylor R, editor. Herbicides in Asian rice agriculture. Los Baños (Philippines): International Rice Research Institute. p 3-26.

Oerke EC. 2006. Crop losses to pests. J. Agric. Sci. 144:31-43.

Ou SH. 1987. Rice diseases. Second Edition. Farnham Royal (UK): C.A.B. International.

Oryza. 2010. China: GM rice to be commercially available soon. http://oryza.com/Global-Rice/Genetically-Modified-Rice/China-GM-Rice-To-Be-Commercially-Available-Soon.html, accessed July 2010.

Padwick GW. 1956. Losses caused by plant diseases in the tropics. Comm. Mycol. Inst. Kew, Surrey, Phytopath. Papers No. 1.

Palis FC, Flor RJ, Warburton H, Hossain M. 2006. Our farmers at risk: behavior and belief system in pesticide use. J. Public Health 28:43-48.

Panda N, Khush GS. 1995. Host plant resistance to insects. Wallingford (UK): CABI.

Pandey S, Velasco L. 2005. Trends in crop establishment methods in Asia and research issues. In: Toriyama K, Heong KL, Hardy B, editors. Rice is life: scientific perspectives for the 21st century. Los Baños (Philippines): International Rice Research Institute and Tsukuba (Japan): Japan International Research Center for Agricultural Sciences. p 178-181.

Pennsylvania State University. 2009. http://paipm.cas.psu.edu/154.htm, accessed 30 December 2009.

PhilRice. 2010. PalayCheck system for the Philippine irrigated lowland rice. Pinoy Rice Knowledge Bank. www.pinoyrkb.com/main/, accessed June 2010.

Pingali PL, Gerpacio RV. 1997. Towards reduced pesticide use for cereal crops in Asia. CIMMYT Economics Working Paper 97-04. Mexico, D.F.: CIMMYT.

2010. Pp 297 - 332. Ch 2.5. In " Rice in the global economy: strategic research and policy issues for food security. (eds) S. Pandey, D Byerlee, D Dawe, A Dobermann, S. Mohanty, S. Rozelle, and B. Hardy. Los Banos; Philippines. International Rice Research Institute. 477 p.

Pingali PL, Marquez CB, Palis FG. 1994. Pesticides and Philippine farmer health: a medical and economic analysis. Am. J. Agric. Econ. 76:587-594.

Pingali PL, Roger PA, editors. 1995. Impact of pesticides on farmer health and the rice environment. Norwell, Mass. (USA) and Los Baños (Philippines): Kluwer Academic Publishers and the International Rice Research Institute.

Pinstrup-Andersen P, de Londono N, Infante M. 1976. A suggested procedure for estimating yield and production losses in crops. PANS 22:359-365.

Rao AN, Johnson DE, Sivaprasad B, Ladha JK, Mortimer AM. 2007. Weed management in direct-seeded rice. Adv. Agron. 93:153-255.

Ricker-Gilbert J, Norton GW, Alwang J, Miah M, Feder G. 2008. Cost effectiveness of alternative integrated pest management extension methods: an example from Bangladesh. Rev. Agric. Econ. 30(2):252-268.

Rogers E. 1995. Diffusion of innovations. New York (USA): The Free Press.

Rola AC, Pingali PL. 1993. Pesticides, rice productivity, and farmers' health: an economic assessment. Los Baños (Philippines): World Resources Institute and the International Rice Research Institute.

Rubia EG, Heong KL, Zalucki M, Gonzales B, Norton GA. 1996. Mechanisms of compensation of rice plants to yellow stem borer *Scirpophaga incertulas* (Walker) injury. Crop Prot. 15:335-340.

Savary S, Elazegui FA, Teng PS. 1998. Assessing the representativeness of data on yield losses due to rice diseases in tropical Asia. Plant Dis. 82(6):705-709.

Savary S, Willocquet L, Elazegui FA, Teng PS, Du PV, Zhu D, Tang Q, Huang S, Lin X, Singh HM, Srivastava RK. 2000a. Rice pest constraints in tropical Asia: characterization of injury profiles in relation to production situations. Plant Dis. 84:341-356.

Savary S, Willoquet L, Elazegui FA, Castilla NP, Teng PS. 2000b. Rice pest constraints in tropical Asia: quantification of yield losses due to rice pests in a range of production situations. Plant Dis. p 357-369.

Savary S, Teng PS, Willocquet L, Nutter Jr FW. 2006a. Quantification and modeling of crop losses: a review of purposes. Annu. Rev. Phytopathol. 44:89-112.

Savary S, Mille B, Rolland B, Lucas P. 2006b. Patterns and management of crop multiple pathosystems. Eur. J. Plant Pathol. 115:123-138.

Schoenly K, Cohen JE, Heong KL, Arida G, Barrion AT, Litsinger JA. 1995. Quantifying the impact of insecticides on food web structure of rice arthropod populations in Philippines farmers' irrigated fields. In: Polis GA, Winemiller K, editors. Food webs: integration of patterns and dynamics. London (UK): Chapman and Hall. p 343-351

Singh VP, Singh G, Singh Y, Mortimer M, Johnson DE. 2008. Weed species shifts in response to direct seeding in rice. In: Singh Y, Singh VP, Chauhan B, Orr A, Mortimer AM, Johnson DE, Hardy B, editors. Direct seeding of rice and weed management in the irrigated rice-wheat cropping system of the Indo-Gangetic Plains. Los Baños (Philippines): International Rice Research Institute and Pantnagar (India): Directorate of Experiment Station, G.B. Pant University of Agriculture and Technology. p 213-219.

Singleton GR. 1997. Integrated management of rodents: a Southeast Asian and Australian perspective. Belgian J. Zool. 127:157-169.

Singleton GR. 2003. Impacts of rodents on rice production in Asia. International Rice Research Institute Discussion Paper Series No. 45. Los Baños (Philippines): International Rice Research Institute. 30 p.

Singleton GR, Sudarmaji, Jacob J, Krebs CJ. 2005. Integrated management to reduce rodent damage to lowland rice crops in Indonesia. Agric. Ecosyst. Environ. 107:75-82. DOI: 10.1016/j.agee.2004.09.010.

2010. Pp 297 - 332. Ch 2.5. In " Rice in the global economy: strategic research and policy issues for food security. (eds) S. Pandey, D Byerlee, D Dawe, A Dobermann, S. Mohanty, S. Rozelle, and B. Hardy. Los Banos; Philippines. International Rice Research Institute. 477 p.

Singleton GR, Brown PR, Jacob J, Aplin KP, Sudarmaji. 2007. Unwanted and unintended effects of culling: a case for ecologically-based rodent management. Integr. Zool. 2:247-259.

Southwood TRE, Comins HN. 1976. A synoptic population model. J. Anim. Ecol. 45:949-965.

Stenseth NC, Leirs H, Skonhoft A, Davies SA, Pech RP, Andreassen HP, Singleton GR, Lima M, Machangu RM, Makundi RH, Zhang Z, Brown PB, Shi D, Wan X. 2003. Mice and rats: the dynamics and bioeconomics of agricultural rodent pests. Front. Ecol. Environ. 1:367-375.

Tejada AW, Magallona ED. 1985. Fate of carbosulfan in a rice paddy environment. Philipp. Entomol. 6:255-273.

Teng PS. 1994. Integrated pest management in rice. Exp. Agric. 30:115-137.

Tjornhom JD, Norton GW, Heong KL, Talekar NS, Gapud V. 1997. Determinants of pesticide misuse in Philippine onion production. Philipp. Entomol. p 139-149.

Tjornhom JD, Norton GW, Gapud V. 1998. Impacts of price and exchange rate policies on pesticide use in the Philippines. Agric. Econ. 18:167-175.

Tuong TP, Bouman BAM, Mortimer M. 2005. More rice, less: water: integrated approaches for increasing water productivity in irrigated rice-based systems in Asia. Plant Prod. Sci. 8:231-241.

UNEP-WCMC (United Nations Environmental Programme World Conservation Monitoring Centre). 2007. Biodiversity and poverty reduction: the importance of biodiversity for ecosystem services. Cambridge (UK): UNEP-WCMC.

Waage J. 1989. The population ecology of pest-pesticide-natural enemy interactions. In: Jepson P, editor. Pesticides and non target invertebrates. Wimborne, Dorset (UK): Intercept. p 81-94.

Wang Y, Zhang G, Du J, Liu B, Wang M. 2010. Influence of transgenic hybrid rice expressing a fused gene derived from *cry1Ab* and *cry1Ac* on primary insect pests and rice yield. Crop Prot. 29:128–133.

Way MJ, Heong KL. 1994. The role of biodiversity in the dynamics and management of insect pests of tropical irrigated rice: a review. Bull. Entomol. Res. 84:567-587.

weedscience.org. 2009. Resistant weeds. www.weedscience.org/Summary, accessed 12 December 2009.

Willocquet L, Elazegui FA, Castilla N, Fernandez L, Fischer KS, Peng S, Teng PS, Srivastava RK, Singh HM, Zhu D, Savary S. 2004. Research priorities for rice disease and pest management in tropical Asia: a simulation analysis of yield losses and management efficiencies. Phytopathology 94(7):672-682.

Wopereis MCS, Defoer T, Idinoba P, Diack S, Dugué MJ. 2009. Participatory learning and action research (PLAR) for integrated rice management (IRM) in inland valleys of sub-Saharan Africa: technical manual. www.warda.org/warda/guide-plar-tech.asp.

Xuyen K, Hoi NC, Trung PQ. 1998. Occupational environment and skin diseases in pesticide exposed subjects in some tea farms in Vietnam. Paper presented to the Third National Scientific Conference on Occupational Health, Hanoi, 4-5 December 1998.

Zadoks JC. 1985. On the conceptual basis of crop loss assessment: the threshold theory. Annu. Rev. Phytopathol. 23:455-473.

Zadoks JC, Schein RD. 1979. Epidemiology and plant disease management. New York (USA): Oxford University Press.

Zeigler RS, Savary S. 2009. Plant disease and world dependence on rice. In: Strange RN, Gullino ML, editors. The role of plant pathology in food safety and food security, plant pathology in the 21st century. Springer Science+Business.

2010. Pp 297 - 332. Ch 2.5. In " Rice in the global economy: strategic research and policy issues for food security. (eds) S. Pandey, D Byerlee, D Dawe, A Dobermann, S. Mohanty, S. Rozelle, and B. Hardy. Los Banos; Philippines. International Rice Research Institute. 477 p.

## Notes

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