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Contents

Abstract

Several opportunities are available for dramatically reducing the use of agrochemicals in Asian cereal crop production. The first section of this paper summarizes past trends and future prospects for pesticide use in Asia for the three major cereal crops: rice, wheat, and maize. The second section identifies factors that have contributed to rising farm-level demand for pesticides and factors that could lead to a reduction in their demand. The third section highlights the advances that have been made in generating and disseminating cereal crops with resistance to insects and diseases. It focuses on conventional breeding strategies for host-plant resistance as well as the current and potential contributions of biotechnology. Pesticide productivity, yield variability, and their relation to host-plant resistance are reviewed, along with evidence from trials and farmers' fields. The paper concludes with a discussion of the integrated management approaches that will be necessary for maximizing and sustaining the productivity gains offered by resistant varieties.

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Introduction

Intensive crop monoculture systems, popularized by the Green Revolution, created an environment that was conducive to pest growth. Although pest-related yield losses were small in percentage terms, they were highly visible and led to apprehension that major outbreaks would occur (Rola and Pingali 1993). Policy makers' aversion to large-scale pest outbreaks resulted in policies that made pesticides easily accessible and affordable at the farm level (Pingali and Rola 1995). Pesticides were seen as a complement to crop production, serving both as a guarantee against crop failure and as a means of fully utilizing the yield potential of the crops (Waibel 1986). While frequent and indiscriminate pesticide use is the norm in developing countries today, farm-level promotion of pesticides is accompanied by little, if any, information about their judicious use, farmer safety, and adverse ecological and health consequences of pesticides.

Indiscriminate pesticide use in the production of various crops has been documented to have resulted in one or more of the following:

- health impairment resulting from direct or indirect exposure to hazardous chemicals;
- contamination of ground and surface water through runoff and seepage;
- the transmittal of pesticide residues through the food chain;
- increased resistance of pest populations to pesticides, which reduces their efficacy and leads to pest outbreaks; and
- the reduction of populations of beneficial insects such as parasites and predators, which reduces the effectiveness of pest control strategies that attempt to minimize pesticide use (see Pingali and Roger, 1995, for rice; Cornwell, 1995, tobacco; Crissman and Cole, 1994, potato; and Forget, Goodman, and de Villiers 1993).

Technological change is dramatically reducing the need for pesticide use in cereal crop production systems. Today, with improved host-plant resistance, improved crop management, and advances in integrated pest management, along with a reformed policy environment that is beginning to discourage pesticide use, the link between pesticides and cereal crop productivity has become less clear. Certainly in the case of insecticides for rice and fungicides for wheat, recent evidence indicates that the productivity benefits of applying chemicals are marginal at best. In the case of maize, the use of chemicals in subsistence production systems has always been low. Commercialization of these production systems has led to increased pesticide use. However, in recent decades, maize varieties with improved resistance to insects and diseases have been developed. The one uncertainty for the future of chemical use is herbicides. Adequate nonchemical controls for weeds are not yet available, and herbicide use is increasing dramatically as a result of rising opportunity costs of labor across the developing world.

This paper describes the opportunities currently available for a dramatic reduction in agrochemical use in cereal crop production systems in Asia. The first section summarizes past trends and future prospects for pesticide use in Asia for the three major cereals, rice, wheat, and maize. The second section identifies factors that contributed to the rise in farm-level demand for pesticides and factors that could lead to a reduction in their demand. The third section highlights the advances that have been made in generating and disseminating cereal crops with resistance to insects and diseases. The final section discusses the integrated management approaches that will be necessary for maximizing and sustaining the productivity gains offered by resistant varieties.

The Pesticide Market and Pesticide Use in Asian Cereal Production

Rising from US$ 900 million in 1960, the global agricultural pesticide market was valued at US$ 27.5 billion in 1993 and US$ 30.3 billion in 1995, indicating an annual growth rate of almost 11%. Global pesticide sales in 1993 were equivalent to almost two million tons of active ingredients, of which 497,000 t (25%) was consumed in Asian agriculture (FAO 1997). Cereal crop production across the world is reported to be the second largest consumer of agricultural pesticides, surpassed only by fruit and vegetable production. In 1995, rice and maize production consumed about 23% of all agrochemicals, while fruit and vegetables accounted for about 26% (IFPRI 1996). Global rice production consumed about US$ 3.2 billion worth of agricultural pesticides (12% of 1993 pesticide sales), of which US$ 2.6 billion (81%) was spent in Asia.

Before the 1960s, pesticides were consumed mostly in industrialized nations. With agricultural modernization in developing countries in the mid-1960s, exports to the Third World became an important part of the global pesticide industry. In the 1960s and 1970s, the United States, Britain, Germany, France, Switzerland, Italy, and Japan accounted for 75% of world chemical production and provided approximately 85% of all agrochemicals used in Asia (Boardman 1986, UN 1990, as cited in Pingali and Rola 1995).

A large proportion of the pesticides exported to the developing countries consists of products that are no longer used in the developed countries on experimental and health grounds. Weir and Shapiro (1981), for instance, pointed out that at least 25% of US pesticide exports are products that are banned, heavily restricted, or have never been registered for use in the United States. Warburton, Palis, and Pingali (1995) also reported that the vast majority of insecticides used in developing Asian countries were classified as highly hazardous category I and II chemicals by the World Health Organization and that many of them have been banned for agricultural use in most developed countries. These insecticides include the organochlorine, endosulfan; organophosphates, such as methyl parathion, monocrotophos, and chlorpyrifos; carbamates, such as BPMC, carbaryl, and carbofuran; and pyrethroids such as cypermethrin and deltamethrin. However, these chemicals continue to be widely used in tropical Asia, either because of ignorance or substantially lower costs compared to safer alternatives.

Both the type and quantity of pesticides used vary considerably from country to country and crop to crop. Herbicides dominate North American and European domestic markets, but insecticides are more commonly used elsewhere in the world, especially in the Asia-Pacific region. The share of East Asia in global pesticide consumption was 14%, but this region accounted for 54% of Asia's pesticide use. Wood Mackenzie Ltd. (1993, cited in IRRI 1995) reported that, in 1993, Japan alone accounted for 62% of all pesticides used in Asian rice production: 46% of the region's rice insecticides, 71% of herbicides, and 72% of its fungicides (Table 1). The next largest users of rice pesticides in Asia are South Korea, China, and India, at 12%, 11%, and 7% respectively.

Aggregate figures, though, tend to mask the intensity of pesticide use. Malaysia accounts for just 9% of Asian pesticide consumption but is the region's most intensive user of pesticides, applying 23.42 kg active ingredient per hectare (kg ai/ha) of arable land. On the other hand, India consumed 14% of all agricultural pesticides in Asia but applied only about 0.43 kg ai/ha of arable land.

In Asian cereal crop systems, insecticides are predominantly used for rice and commercial maize production. Almost none are used in wheat production. Fungicides are generally not important for cereal crops, except for rice in the East Asian countries. Fungicide use on rice in the rest of Asia may increase if the current push towards higher rice yields is pursued (Pingali, Hossain, and Gerpacio 1997). In the case of wheat, the plant's ability to resist high levels of disease pressure has made fungicide use almost obsolete in Asian wheat production systems (further details are provided later in this paper). Herbicide use on all three cereals has grown as rising agricultural wages, the result of increasing off-farm employment opportunities, have reduced the cost-effectiveness of hand weeding (Naylor 1997).

Although Asian rice production remains the major consumer of agricultural pesticides, it should be noted that the composition of the Asian pesticide market has been changing in recent years. The proportion of insecticides used in Asian rice production, for example, decreased from about 45% of all pesticides in 1984 to 37% in 1993 (Table 2). Total insecticide

Table 1. Share in consumption of pesticides used in rice production, selected Asian countries, 1993 (computed based on rice pesticide sales)

Country	Insecticides	Herbicides	Fungicides	All pesticides
Bangladesh	1.03	0.54	1.38	0.95
China	16.55	8.67	7.59	11.22
India	12.41	2.49	4.14	6.58
Indonesia	4.14	0.65	0.69	1.94
Japan	45.60	71.40	72.41	61.81
Korea, Republic of	13.24	11.92	11.31	12.17
Myanmar	1.03	0.54	0.69	0.76
Philippines	1.55	1.19	0.41	1.10
Thailand	2.48	1.95	0.69	1.79
Vietnam	1.96	0.65	0.69	1.14

Source: Constructed from data in IRRI (1995).

use for rice production actually fell by 10% from 1989 to 1993 (Table 3). Over the same period, the proportion of herbicides in total chemical use increased from 27% to 35%. Herbicide use grew at a rate of about 4% per year during 1987-92.

In 1984, rice production in China used 64% insecticides, 8% herbicides, and 28% fungicides; by 1993, insecticide use had dropped to 54% while herbicide use had risen to 27% of all pesticide use. India and the Philippines demonstrated the same trend of pesticide consumption in rice production. In contrast, rice economies with cheap agricultural labor, such as Vietnam and Myanmar, still show an increasing use of insecticides in rice production, although the use of herbicides is decreasing (Table 2).

Table 2. Percentage of insecticides, herbicides, and fungicides used in rice production, selected Asian countries, 1984-93

Country/region	Insecticides	Herbicides	Fungicides
Bangladesh			
1984	61.3	19.4	19.4
1988	42.6	27.7	29.8
1993	40.0	20.0	40.0
China			
1984	64.3	7.8	27.9
1988	77.9	4.2	17.9
1993	54.2	27.1	18.6
India			
1984	79.1	9.4	11.5
1988	77.1	12.1	10.8
1993	69.4	13.3	17.3
Japan			
1984	29.8	37.4	32.8
1988	32.1	40.7	27.1
1993	27.1	40.6	32.3
Philippines			
1984	59.5	24.3	16.2
1988	37.5	37.5	25.0
1993	51.7	37.9	10.3
Myanmar			
1984	36.4	45.5	18.2
1988	33.3	33.3	33.3
1993	50.0	25.0	25.0
Vietnam			
1984	50.0	33.3	16.7
1988	30.8	38.5	30.8
1993	63.3	20.0	16.7
Asia			
1984	44.5	26.8	27.6
1988	42.1	31.4	25.7
1993	36.8	35.1	27.6

Source: Constructed from data in IRRI (1995).

Indiscriminate and injudicious use of agrochemicals in developing countries was a direct result of inappropriate or inadequate pesticide policies. An enlightened policy environment, along with the introduction of crop varieties resistant to insects and diseases and the promotion of integrated pest management, has generally resulted in reduced pesticide use, the use of safer chemicals, and improved farmer safety and environmental sustainability.

Table 3. Percentage change in and growth of sales of insecticides, herbicides, and fungicides used in rice production, selected Asian countries, 1980-93

	Percentage change			Growth rate (%/yr)	
Country/region	**1980-84**	**1985-89**	**1990-93**	**1981-86**	**1987-92**
Bangladesh					
Insecticides	..	-37.5	-66.7	..	-6.3
Herbicides	..	0.0	-66.7	..	-6.1
Fungicides	..	33.3	-47.4	..	6.8
China					
Insecticides	109.1	17.9	-8.6	12.0	4.4
Herbicides	40.0	-37.5	..	9.0	..
Fungicides	31.6	0.0	22.2	1.2	2.1
India					
Insecticides	175.0	13.8	-28.6	8.5	4.4
Herbicides	62.5	53.3	-17.9	9.3	9.4
Fungicides	14.3	33.3	25.0	0.4	11.9
Japan					
Insecticides	62.3	51.9	1.4	14.6	-1.1
Herbicides	6.8	53.4	14.6	11.6	1.0
Fungicides	3.1	16.6	34.6	11.0	1.9
Philippines					
Insecticides	37.5	-40.0	-21.0	7.4	0.0
Herbicides	125.0	40.0	-21.4	17.6	2.5
Fungicides	0.0	83.3	-78.6	1.1	12.0
Myanmar					
Insecticides	4.0	167.9	36.2	7.3	15.5
Herbicides	0.0	83.3	155.8	16.0	31.6
Fungicides	0.0	191.7	-6.8	8.7	9.9
Vietnam					
Insecticides	20.0	-16.7	58.3	3.3	10.4
Herbicides	..	20.0	-50.0	..	0.0
Fungicides	..	150.0	-58.3	..	13.6
Asia					
Insecticides	77.9	36.4	-10.4	11.5	3.3
Herbicides	23.0	46.0	24.4	13.0	3.7
Fungicides	12.8	35.5	10.2	9.4	4.2

Source: Constructed from data in IRRI (1995).
Note: .. = data not available.

Agricultural Modernization and the Demand for Agrochemicals

In the developing world, agricultural modernization, which is meant to include agricultural intensification and increased market orientation, has spurred rapid growth in the demand for agrochemicals. The Green Revolution in cereal crop production, especially in Asia during the late 1960s and the 1970s, led to an upward shift in the demand for modern agricultural inputs, including pesticides. Although demand for pesticides as a whole grew very quickly, an examination of the trends for chemical subgroups (insecticides, herbicides, and fungicides) indicates that there was substantial variation by country or region and by crop. Pingali and Rola (1995) have provided a stylized representation of the factors leading to regional differences in pesticide use, which is summarized here.

Agricultural intensification — the movement from an extensive to an intensive production system, or from a subsistence production system to a commercial one — has been extensively documented to have promoted increased use of agrochemicals. Table 4 shows the differential effects of increasing land scarcity and increasing market orientation on the demand for chemicals. Consider first a sparsely populated subsistence society with limited access to markets. Agriculture in such societies is characterized by extensive land use and an almost complete reliance on nontraded inputs, such as farmyard manure. Pest pressure is low in such systems and is kept that way through a variety of management practices such as crop rotations and the use of traditional cultivars with known resistance to chronic pest problems.

Increasing land scarcity caused by population growth in subsistence societies leads to agricultural intensification — that is, increased intensity of land use (Boserup 1965; Pingali and Binswanger 1987). Where the opportunity costs of family labor are low, food production continues to rely predominantly on nontraded inputs. Pest pressure increases with intensification as pests are carried over both spatially and temporally. Although increased weed pressure is handled by family labor, increased insect pressure is no longer amenable to traditional management practices, and small amounts of insecticides begin to be used for cereal crops, even in subsistence societies. Low to moderate amounts of fungicides also tend to be used on such crops as cotton, tobacco, and horticultural products, especially fruits and vegetables (Table 5).

Table 4. Intensification, market orientation, and demand for agrochemicals

	Market orientation	
Land:labor ratio	**Low**	**High**
High	Low demand for all chemicals	Herbicides predominate
Low	Insecticides predominate	High demand for all chemicals

Source: Rola and Pingali (1995).

The contrasting scenario is one of a sparsely populated area that has excellent access to markets. In this case, agricultural intensification will be high because of high land values, but unlike the subsistence case, the opportunity cost of labor will also be high: hence the high levels of traded input use. Even though increasing insect pressure can be controlled through appropriate crop rotations and seasonal fallows, the dominant constraint is weeds, and high levels of herbicide use are the norm in such societies. High use of fungicide can also be observed for horticultural crops, especially fruit and vegetables. Where market access and land scarcity are both high, high opportunity costs of land and labor result in agricultural intensification with a high use of traded inputs. The demand for all chemicals is high in such societies.

It is also recognized that pesticide use was further aggravated by modern cereal crop production systems. Intensive monoculture systems using high yielding varieties of cereal crops resulted in an environment conducive to pest buildup and infestation, and the consequent use of pesticides disrupted the natural pest-predator balance. The risk of insect- and disease-related losses increased because early modern varieties were often highly susceptible to local pests and because crop heterogeneity was lost. Regular prophylactic pesticide application promoted by extension services and supported by government subsidies became a standard part of the early Green Revolution package.

In addition, because early pesticide formulations were often nonselective, pesticides proved equally lethal to beneficial pests that preyed on crop pests. In many cases, pesticide use actually resulted in lower yields, as crop pests, freed of their natural predators, multiplied without constraints (Pagiola 1995; Rola and Pingali 1993). In the case of rice in tropical Asia, a large number of pest outbreaks have been associated more with injudicious pesticide applications than with the use of modern high yielding cultivars, high cropping intensity, and/or high chemical fertilizer use (Heinrichs and Mochida 1984; Kenmore et al. 1984; Joshi et al. 1992, Schoenly et al. 1996). Outbreaks of secondary pests of rice, notably the brown

Table 5. Agrochemical use by stage of agriculture and cropping

	Cropping system		
Farm characteristics	**Cereal crops (e.g., rice)**	**Other field crops (e.g., cotton, tobacco)**	**Horticultural crops (e.g., fruits, vegetables)**
Land-abundant, subsistence	All chemicals, none	All chemicals, none to low	All chemicals, none to low
Land-scarce, subsistence	Insecticides, low to moderate	Insecticides, fungicides, low to moderate	Fungicides, low to moderate
Land-abundant, market-oriented	Herbicides, moderate to high	Herbicides, fungicides, moderate to high	Fungicides, herbicides, moderate to high
Land-scarce, market-oriented	Insecticides, herbicides, high	All chemicals, high	All chemicals, high

Source: Rola and Pingali (1995).

planthopper, previously of minor significance, began to occur in regions adopting modern varieties and concomitant use of agrochemicals (Pingali and Gerpacio 1997). High and injudicious pesticide applications disrupt the rich diversity of pest and predator populations, where in most instances the species richness and abundance of predator populations may be greater than those of the pest populations.

The rapid growth in pesticide use can also be attributed to the misinformation and risk-aversion of both policy makers and farmers. In an extensive review of rice case studies from across Asia, Rola and Pingali (1993) have documented that policy makers' perceptions of yield losses are higher than farmers' perception of yield losses, which in turn are substantially higher than actual yield losses. Both farmers' and policy makers' perceptions of pest-related yield losses derive from the exceptionally high losses during major infestations, even when the probability of such infestations is low. In minor infestations, physical damage to plants from pests is easily seen but does not always result in yield loss. Heong, Escalada, and Vo Mai (1994) have shown that leaf damage, even as much as 50%, has insignificant effects on rice yields, yet 80% of insecticide applications for rice in Asia are targeted towards leaf-feeding insects.

While in aggregate terms cereal crops account for the bulk of pesticide use in Asia, on a per-hectare basis their use is quite small when compared to the levels applied on fruits, vegetables, and other high value commodities. Pesticide application in high value crops is related to consumer demand for aesthetically appealing agricultural products. Since these high value agricultural products enjoy a substantial price premium for an unblemished physical appearance, risk-averse farmers tend to apply pesticides beyond the technical optimum to capture this price differential. Pagiola (1995), for example, reports that in Bangladesh, where 70% of pesticides are used on rice, the amounts used per unit area and the total area affected are both relatively small. The use of insecticides on vegetables, however, follows a pattern almost diametrically opposed to that found in rice. Whereas rice is sprayed only two to three times a season, it is common to spray vegetables such as eggplant and country beans several times a week. A survey of eggplant producers in Jessore indicated a range of application from 17 to 150 times for one crop cycle (Kabir et al. 1994, cited in Pagiola 1995). Rates of insecticide use are lower for other vegetables, but they are still generally higher than for rice. Cauliflower and cabbage, for instance, are commonly sprayed three to four times. In the case of wheat, maize, and rice, pesticides do not enhance physical quality in any way, and there is no price differential to capture (Rola and Pingali 1993). Given the positive income elasticity of demand for fruits and vegetables, the long-term prognosis for developing economies is one of increasing area under these crops and, in the absence of alternative pest control strategies, on an increasing share of the agrochemical market (Pingali and Rola 1995).

With recent advances in developing cereal crops' tolerance of insects and diseases and in integrated pest management strategies, the outlook for future reductions in pesticide use is very promising. Modern science has helped reduce the dependence on insecticides for rice and maize and the dependence on fungicides for wheat. The dependence on herbicides for cost-effective weed management continues to be problematic, with little scientific advance either on the genetic or the crop management side.

Breeding for Host-Plant Resistance as a Technological Alternative to Pesticides

Host-plant resistance, i.e., a plant's ability to resist high levels of pest infestation, has been the cornerstone of the scientific strategy for developing sustainable pest control systems for cereal crops. Significant advances have been made in the last three decades in the development and dissemination of crop varieties with resistance to the major cereal pests (Table 4). Many of these advances have come through conventional breeding approaches, although substantial future gains in resistance could come through modern biotechnology tools. Host-plant resistance ought to be seen as an essential building block in an integrated pest management strategy. Attempts to promote resistant varieties without a concomitant change in pesticide management practices have generally failed as a result of early breakdowns in resistance.

Conventional Breeding for Host-Plant Resistance

Although they may be tedious and time-consuming, conventional breeding techniques have led to significant progress in generating varieties resistant to major insect pests and diseases. Early work at the International Rice Research Institute (IRRI), Philippines, found that most of the important sources of resistance to major diseases and pests had been incorporated into modern rice varieties (IRRI 1972). The emphasis on releasing rice varieties with improved host-plant resistance to major insect and disease pressures has continued through subsequent decades (Table 6). Lines considered promising have been named as varieties, whereas others have proven to be good parents in new crosses. Named varieties and promising breeding lines provide resistance to important rice insect pests such as green leafhopper, brown leafhopper, stemborers, and gall midge and to diseases such as blast, bacterial leaf blight, bacterial leaf streak, tungro, and grassy stunt (IRRI 1985).

For wheat and maize, the International Maize and Wheat Improvement Center (CIMMYT), based in Mexico, has active research programs to develop desirable levels of disease and insect resistance (note that insect problems are not as important in wheat as in maize and rice). CIMMYT combines "shuttle breeding" (for wheat), "hot spot" screening, and multilocational

Table 6. The evolution of host-plant resistance for the major cereal crops

Period	Rice	Wheat	Maize
1960s	Striped stemborer	Stem rust	European corn borer
1970s	Brown planthopper Green leafhopper Rice whorl maggot	Septoria tritici bloth	Earworms Tropical borers Southwestern corn borer
1980s	Yellow stemborer White-backed planthopper Brown planthopper Thrips	Leaf rust	Fall armyworm
1990s	*Bacillus thuringiensis*	Spot blotch Fusarium scab Stripe rust	*Bacillus thuringiensis*

testing within Mexico and abroad to obtain resistance to multiple diseases for the different agroecological zones (“megaenvironments”) where wheat and maize are grown (Dubin and Rajaram 1996). “Shuttle breeding” refers to a method in which breeding generations from the same crosses are alternately selected in environmentally contrasting locations as a way of combining desirable characters. “Hot spots” are locations where significant variability for a pathogen exists, and where plants can be screened in the presence of as broad a range of virulence genes and combinations as possible. This screening, together with multilocational testing, increases the probability of developing durable resistance.

In wheat, considerable genetic progress has been achieved in developing host-plant resistance to leaf rust, septoria leaf blotch, fusarium scab, and bacterial leaf streak in the high rainfall areas of the tropical highlands. Some progress has also been made in achieving resistance to the second-priority diseases, barley yellow dwarf, tan spot, and septoria nodorum blotch (Table 6; Dubin and Rajaram 1996).

In the case of maize, most of the released hybrids and composites have high resistance to foliar diseases, and breeding for resistance to prevalent insect pests and diseases has made considerable progress (CAB 1980). More recently, Kumar and Mihm (1995) found that CIMMYT had developed potentially useful single-cross hybrids and varieties (e.g., CML 139 x CML 135, CML 139 x K_i3, CML 67 x CML 135), which suffered less damage and percentage grain yield loss to fall armyworm, southwestern corn borer, and sugarcane borer because of their improved resistance compared to earlier varieties. The screening of CIMMYT germplasm bank accessions and elite germplasm has also continued to identify new or better sources of maize resistance to stemborers, armyworm, maize weevils, spider mites, rootworms, and corn earworms (Mihm et al. 1994, cited in Edmeades and Deutsch 1994).

Thus for decades plant breeders have ensured that each new elite cultivar and breeding line possesses a wide range of genes for resistance to pests and diseases. However, breeding programs are challenged by the fact that genetic variation is not confined to the host plant but is also a feature of the pest or parasite. With certain types of resistance, selection for a resistant population of the host is closely followed by natural selection of the pest or parasite for those variants that can overcome the resistance. The risk is greater when large areas are planted year-long to a single, homogeneous cultivar and when pesticide use is indiscriminate. Pest and pathogen populations change over time, and genetic resistance breaks down, while some pest and disease problems remain intractable. To keep ahead of evolving and changing pest populations, breeding activities must constantly aim to increase genetic diversity against pests and develop cultivars with more durable resistance. Recent advances in biotechnology can help improve the durability of host-plant resistance.

Contributions of Biotechnology to Breeding for Host-Plant Resistance

Biotechnology adds a new dimension to the research for improved host-plant resistance by enhancing conventional breeding efforts through the use of wide hybridization, molecular marker technologies, and genetic engineering. Biotechnology enhances the efficiency of conventional breeding by reducing the length of the breeding process and the inherent trial-and-error nature of conventional breeding. Biotechnology may also lead to enhanced durability of resistance through the incorporation of alien and novel genes into cultivated plant species. In the short to medium term, the contributions of biotechnology are likely to be most significant in improving the durability of pest resistance, rather than contributing to yield and grain quality improvement. The following is a brief discussion of the prospects of biotechnology for the major cereal crops.

Wide hybridization allows breeders to use genetic diversity drawn from the wider gene pool of a crop's entire genus. A crucial tissue culture technique, embryo rescue, enables breeders to cross cultivated species with wild species or distant relatives and allows faster stabilization of select breeding lines in the laboratory, rather than through actual field cultivation. Pieces of the wild genome are integrated into the chromosomes of the elite parents, useful genes are transferred from different wild species into cultivated varieties, and the progeny are readily stabilized.

Embryo rescue has produced hybrids between cultivated rice and 12 wild species. Genes for resistance to brown planthopper, white-backed brown planthopper, bacterial blight, and blast have already been transferred from wild species into elite rice breeding lines (IRRI 1993b).

Diversity for resistance and/or tolerance to several stresses under prevailing conditions in Mexico is now available in wheats developed through wide hybridization. Resistance to Karnal bunt, septoria tritici blotch, and spot blotch, obtained through wide hybrid wheats and based on disease screening data obtained over several years, is being utilized for bread wheat improvement. Resistant wheat genetic stocks developed through wide hybridization have now been crossed onto elite cultivars, and the resulting lines are also expressing diversity for resistance to these three diseases. This germplasm is being incorporated into advanced bread wheat lines to diversify the genetic base of resistance/tolerance to other stresses as well (Pingali and Rajaram 1997).

Molecular marker technology increases the efficiency with which specific desirable genes are combined into improved breeding lines, by facilitating gene selection. A genetic map is used to show the relative position of genes on a chromosome and the distance between genes. The position of useful and important genes on the chromosomes is roughly identified or tagged by the use of molecular markers, allowing plant breeders to use indirect selection for genes of interest. Instead of selecting progeny having the gene of interest by checking for the action of the gene, through marker-assisted selection researchers can select directly for the plants having the gene through the presence of the linked marker in the plant's DNA. Such markers are especially useful in breeding for resistance to nonendemic pests and diseases or for incorporating genes with overlapping effects which can contribute to complex and more durable resistance.

In rice, more than 20 single genes for disease and insect resistance have been located relative to the restriction fragment length polymorphism (RFLP) markers. Among these genes are several for resistance to rice blast fungus and major resistance genes for bacterial blight and three insect pests (brown planthopper, white-backed brown planthopper, and gall midge). In wheat, a current project aims to use marker-assisted selection to develop resistance to barley yellow dwarf virus, which affects wheat as well as rice and barley.

Genetic engineering is a process that includes the identification and incorporation of economically valuable genes into a specific crop (these genes may originate from any living organism, virus, or even chemical synthesis), the delivery systems to introduce the desired gene into the recipient cells, and the expression of the new genetic information in the recipient cells. Plant genetic engineering techniques provide breeders with new opportunities to improve the efficiency of production and increase the utility of agricultural crops. Modern varieties could be further improved by inserting foreign genes into plant cells and regenerating viable, stable, and fertile plants that possess useful traits such as disease and insect resistance, better grain quality, and resistance to certain herbicides. Perhaps the biggest advantage of these techniques is that they have the potential to shorten the time that is usually required to develop improved traits in wheat plants.

The first group of useful foreign genes to be inserted into rice included soybean trypsin inhibitor for insect resistance and two barley genes, chitinase and ribosome inhibitor protein (RIP), for resistance to the fungal diseases sheath blight and blast (IRRI 1993a). When introduced into rice, novel genes such as the *Bacillus thuringiensis* (*Bt*) gene for insect resistance and coat protein genes for tungro resistance should impart high levels of resistance. Coat-protein-induced virus resistance is directed against the rice tungro virus (Beachy et al. 1989), the most important disease problem for rice (Herdt and Riley 1987). A coat-protein-mediated resistance to rice stripe virus (an insect-transmitted virus) has been introduced in Japonica rice (Hayakaya et al. 1992). The *Bt* genes are targeted against stemborer (Joos and Morrill 1989), the most important insect pest of rice (Herdt and Riley 1987). Insect resistant rice developed by introducing a modified endotoxin gene of *Bt* has been shown to produce *Bt* protein and enhance insect resistance in Japonica rice (Fujimoto et al. 1993).

Genes for resistance to viral, bacterial, fungal, and other diseases have been identified and successfully transferred into many crops (Ahl Goy and Duesing 1995; Persley 1990). The first genetically engineered Indica rice based on the protoplast system (Datta et al. 1990) now provides sheath blight resistance in Indica rice (Lin et al. 1995). Several chitinase genes in combination with *Bt* genes have been introduced into rice to further enhance protection against pathogenic fungi, bacteria, and insects. The identification of many other genes that may enhance the genetic yield potential of rice or confer resistance to biotic and abiotic stresses is still at an early stage. After their identification, these genes have to be isolated and constructed in a manner suitable for their introduction and expression in the rice genome.

In the case of maize, genetically engineered plants for resistance to corn borer have been produced using *Bt* genes. Though the transformation of wheat plants is still in its infancy, there are significant hopes of developing additional transgenic plants with fungal resistance and abiotic stress tolerance.

While progress in biotechnology is rapid, agronomically viable plants have been developed only in a few cases. Although some progress has been made, gene mapping techniques remain slow and in need of refinement to facilitate marker-assisted gene selection (N. Huang, IRRI, 1995, pers. comm.). The procedure is expensive and requires highly trained personnel. Traditional plant breeding problems are resolved, but challenges facing plant improvement programs essentially remain the same. The germplasm still needs to be screened for desirable genes, which then have to be transferred to the crop, and the performance of the improved plant still has to be tested in the field. In addition, a sound assessment of the usefulness of genetic engineering techniques requires an understanding of possible negative consequences. One example is the incorporation of a gene for herbicide resistance into cereal crops. A herbicide resistant plant could sustain crop productivity in the face of increasing weed competition, especially in direct-seeded and minimum tillage systems, but widespread use of such plants could increase the risk of cross pollination of the gene into weed and wild species, which would aggravate rather than reduce the problem of weed competition. To date, however, there is no evidence that such cross pollination has occurred. A herbicide resistant plant could also encourage high levels of herbicide use and thereby contribute to increased environmental pollution. On the other hand, a herbicide resistant plant could encourage the switch to smaller doses of safer herbicides. There are also a whole host of intellectual property issues to be dealt with in the transfer of genes and advanced biotechnology tools from advanced laboratories to developing country research programs, where they would be used for developing improved cereal crops.

Pesticide Productivity, Yield Variability, and Host-Plant Resistance: Evidence from Experimental Trials and Farmers' Fields

On-farm experiments and examination of farmers' yields do not suggest that there is a yield or profitability response to pesticide applications on resistant crop varieties. The introduction of varieties with host-plant resistance has dramatically reduced the need for insecticides in rice and maize and the need for fungicides in wheat. Evidence for the three major cereals, discussed below, indicates that crop losses from insects and diseases have dropped over the last two decades and that yield losses occurring when chemicals are not applied have declined significantly.

Data on rice crop losses from insect pests in the Philippines, summarized by Rola and Pingali (1993), indicate that estimated crop losses have decreased since the late 1960s and early 1970s. Pathak and Dyck (1973) recorded a crop loss of 22.5% during 1968-72, but more recently both Litsinger (1991) and Waibel (1986) recorded losses of only 8.6 and 8.9%, respectively. The drop in insect-related crop losses could be attributed to the widespread use of resistant cultivars in farmers' fields after the mid-1970s. Both Litsinger and Waibel observed no significant yield differences between insecticide-treated and untreated plots in more than half of the trials. In other words, half of the time farmers need not spray against rice pests, especially on varieties with notable host-plant resistance. Elsewhere we have reported that in farmers' fields the rice yield response to insecticide application is negligible if farmers have adopted resistant varieties (Pingali and Gerpacio 1997). Prophylactic insecticide application on resistant varieties tends to increase rather than decrease variability in crop yields by disrupting the pest-predator balance and inducing a breakdown in resistance.

Host-plant resistance has similarly been successful in the control of major maize insect pests, such as corn borers, corn earworms, and fall armyworm. The use of insecticides on insect-resistant maize varieties has generally not been economically worthwhile. Diseases such as the stem and leaf rusts of wheat, which once caused significant yield losses, have been controlled in the last two decades through improved resistance. Sayre et al. (1997) reported no significant difference in wheat yield in plots sprayed with fungicides and plots where fungicides were not applied, when resistant varieties were used.

The widespread availability of insect and disease resistant varieties for the major cereals has reduced the productivity benefits and the profitability of applying insecticides and fungicides. Discussion of the productivity benefits of pesticides revolves around the assumption that pesticides are a risk-reducing input – in other words, pesticides reduce yield variability. One needs to question this assumption, both for insecticides and fungicides (Pingali and Rola 1995). In the case of insecticide use in rice, Rola and Pingali (1992, 1993) provided empirical evidence that insecticide applications increase yield variability. They estimated an insecticide response function and evaluated the returns to four alternative pest management strategies for the Philippines, using both farm panel data and data from on-farm experiments conducted over several growing seasons. Response function estimates indicated very modest effects of insecticides on the mean and variance of the yield distribution. Comparing the returns to prophylactic control, economic threshold levels, farmers' practice, and natural control, Rola and Pingali found that for lowland tropical rice systems natural control was the economically dominant pest management strategy. Natural control, in association with varietal resistance, proved to be consistently more profitable in an average year than prophylactic treatment and economic thresholds. The dominance of natural control was found to hold even when farmers' risk aversion was accounted for. It becomes even greater when the health costs of exposure to insecticides are explicitly accounted for, because the positive production benefits of applying insecticides are overwhelmed by the increased health costs. The value of crop loss to pests is invariably lower than the cost of pesticide-related illness (Rola and Pingali 1993) and the associated loss in farmer productivity (Antle and Pingali 1994). While such studies have not been conducted for wheat and maize in developing countries, similar results could be anticipated.

The single area where agrochemicals continue to have a significant impact on productivity is in the management of weeds. Herbicides will continue to be the preferred alternative in the foreseeable future. In intensive cereal crop production systems, the use of herbicides is cost-effective relative to the use of human labor, because the seasonality of weeding often creates labor scarcity, and wage rates for weeding surpass those for other crop management operations. The use of herbicides also gained impetus from the general rise in farm wages resulting from overall economic growth and growth in nonfarm employment opportunities, particularly in Asia. As cheap herbicides became available and farm wages rose, cereal crop farmers increasingly substituted herbicides for human labor. The savings in labor cost have more than compensated for the additional cost of herbicides. Pingali and Marquez (1997) have documented the productivity benefits resulting from herbicide use, even when health costs were explicitly accounted for.

There are few genetic and management alternatives to herbicides, and those that exist are generally not very cost-effective. The use of more competitive cereal varieties can avert the effect of weed competition and the consequent use of more herbicides, but there appears to be a trade-off between the plant's ability to compete with weeds and yield (Moody 1991). Research on varietal improvement for weed management in rice is still at a very early stage (Khush 1996). Among the management options for weed control that minimize labor use in rice is the manipulation of water in the paddy (Pingali, Hossain, and Gerpacio 1997). For wheat, potential options include the use of ridge tillage systems (Sayre 1996); for maize, options include cover crops and intercropping. However, none of these options has proven as economically attractive as herbicide use, and the challenge for the research and policy community is to find cost-effective mechanisms for reducing herbicide use in cereal crop production.

The development of genetic resistant to *Striga* spp., the most important weed species in Africa, is an exception to these statements on the lack of success with genetic means for controlling weeds. Approximately 50 million hectares devoted to cereal production in Africa are in areas where *Striga* infestation is a problem. Although three species of the weed are dominant, maximum losses are caused by *Striga hermonthica*. Both tolerance (plants that have lower yield losses compared to susceptible plants) and resistance (plants that prevent attachment of the parasite) are known to exist in maize and other crops. In a recent study (Kim, Adetimirin, and Akintunde 1997), *Striga* was found to reduce maize yields by 25% in tolerant hybrids and 50% in susceptible hybrids over a range of nitrogen levels. Genetic strategies seem to be a viable option to pursue in the pesticide-free management of *Striga*.

Policies for Sustaining a Minimum Pesticide Strategy

Given the extent of breeding efforts to produce pest-resistant crop cultivars and evidence of the insignificant productivity benefits of pesticide use, why do we still see high levels of agrochemical use in crop production? First, the dissemination of crop varieties resistant to pests was not accompanied by extension messages on the need for reduced pesticide use. Second, farmers' pest control decisions, scientists' research priorities, and policy makers' prescriptions, which are all largely based on perceived pest-related yield losses (which in turn are often unrelated to actual yield losses), led to the promotion of pesticide use (Rola and Pingali 1993). Consequently, high and injudicious applications of broad spectrum pesticides continued as before, causing varietal resistance to break down. The resistance of new varieties generated to replace cultivars whose resistance had broken down was also subsequently overcome through further changes in pest populations. This "breeding treadmill" could only be escaped through dramatic changes in crop management practices, especially in the use of pesticides. However, whenever government policies, such as subsidies and credit programs, keep pesticide prices artificially low, the incentives are also low for farmers to invest in knowledge that improves their perceptions and to adopt alternative pest control strategies with a broad ecological approach.

Under low pest infestation levels and when pest-resistant varieties are used, natural control is the economically dominant strategy for managing pests (Rola and Pingali 1993). This is true for insects and diseases for rice, wheat, and maize. Natural control relies on predator populations to control pest infestations in resistant varieties under normal circumstances.

Pesticides may have to be used as a last resort in rare instances when pest infestations are high. Natural control does not imply doing nothing; it is based on the premise of in-depth farmer knowledge of the pest-predator ecology and frequent monitoring of field conditions by the farmer. In this regard, natural control can be considered the ultimate goal of an IPM program, and farmers who are well versed in IPM techniques would converge towards it. For this to happen, there must be a paradigm shift in the traditional IPM strategies, from "when best to apply" to "when not to apply." Therefore continued investments in IPM training are essential for the successful adoption of reduced or minimum insecticide use practices.

Integrated Pest Management

While it is generally recognized that the sustainable use of host-plant resistance requires a more integrated approach to pest management, farm-level pesticide management practices have not changed significantly over the past 20-30 years. Integrated pest management (IPM) practices, for example, have not been well adopted by farmers. Farmers readily accept seed and other tangible crop production technologies, but IPM is knowledge-based, and it presents by far the most difficult challenge to traditional, small-scale farmers in developing countries as they make the transition to scientific farming (IRRI 1994; Goodell 1984). Integrated pest management requires farmers to grasp complex sets of information that are often anything but self-evident, unitary, standardized, or amenable to trial-and-error learning (Goodell 1984). The institutional and economic structure in the rural sector of developing economies also requires some policy intervention to reconcile long-term societal goals and short-term individual objectives in pest control. Promoting sustainable pest management within an IPM framework requires improved research-extension linkages, effective farmer training methods, community action, and an undistorted price structure.

The IPM concept is holistic; it requires farmers to take a systems view of the farm enterprise and understand the many links among the various components of the system. Disseminating such a holistic message requires new sets of skills in extension systems, which traditionally have been geared towards promoting component technologies such as improved seed and fertilizer. Pest and pesticide problems are intrinsically local in nature. National policy ought to nourish the rural community's capacity to handle pest problems effectively, profitably, and equitably. To be successful, the IPM concept needs to be adapted to particular local situations. Such adaptation has to be done with close collaboration of researchers, extension personnel, and farmers. Most IPM success stories have been preceded by research done in farmers' fields, with farmers actively participating in all stages of the research (Escalada and Heong 1993).

The wider dissemination of such locally validated research results requires a decentralized extension system in which the extension message is formulated at the subprovincial or municipality level. In such a system, the extension worker would act as a local researcher adapting research and technology to suit local agroecological conditions and not act merely as an agent for transmitting messages that are barely understood and often inappropriate to the situation at hand. Such a decentralized extension strategy would come about only with a shift away from the current emphasis on top-down information transfer.

Farmer training in sustainable pest management is an essential component of a strategy towards minimum insecticide use. The eventual goal is to build farmers' capacity in identifying and solving problems based on a thorough understanding of field ecology. The experience of the FAO Farmer Field Schools has shown that trained farmers use significantly lower levels of pesticides than untrained farmers (Kenmore 1991). Trained farmers are also more likely to experiment with other components of sustainable production systems, such as improved fertilizer management and more efficient water management.

There are as yet several unresolved research and policy issues related to intensive farmer training in IPM. The most important one is the costs and benefits of such training. The costs of training the 120 million farmers in Asia are enormous and need to be clearly justified in terms of farm-level benefits, both from reduced expenditure on insecticides and reduced social costs of pesticide use. Attention also ought to be focused on the opportunities for reducing overall training costs. There are essentially two options, not mutually exclusive, for reducing training costs. The first is to train a core group of farmers within a geopolitical unit, such as a municipality, and then rely on farmer-to-farmer training for disseminating the IPM message to a wider group of farmers. There are definite scale economies to the farmer-to-farmer training approach, provided the quality of the transmitted message does not deteriorate as it gets passed down the line.

The second approach for a cost-effective transfer of the IPM message is to condense the complex message into several simple rules that farmers can implement easily. An example of such a rule for rice production is, "Do not spray insecticides against leaf-feeding insects for the first 40 days of crop growth." This rule is based on detailed pest ecology studies, which have shown that the predominant insect pests during the first 40 days of crop growth are leaf-feeding insects and that even very high infestations of these insects rarely lead to yield loss (Heong 1990). Leaf-feeding insects are very visible, and farmers tend to attach great importance to controlling them (Heong, Escalada, and Lazaro 1995). Controlling leaf-feeding insects, however, comes at a cost that substantially exceeds the value of yield savings, if any. Insecticide applications early in the growing season tend to wipe out leaf-feeding insects as well as beneficial predator populations that are building up in the paddy. Rice paddies receiving one or two insecticide applications within the first 40 days tend to be susceptible to secondary pest infestations, especially of brown planthopper, which build up unchallenged in the absence of natural controls. Controlling the growth of secondary pests requires further insecticide applications, thus increasing the use of insecticides. By not applying insecticides early in the growing season, farmers can reduce the need for them later, because predator populations will then be abundant in the paddy fields.

The "no spray for 40 days" rule is an example of a simple message, distilled from in-depth research, which can be easily transmitted to farmers. A set of such mutually consistent rules could go a long way towards improving insect pest management in tropical cereal production. Simple rules ought not to be seen as a substitute for farmer training but rather as a strong complement to a training program. Simple messages can be transmitted rapidly even while investments for intensive training continue to be made towards the ultimate goal of reaching all tropical rice farmers.

Community Action

The success of pest management programs depends on, among other things, collective organization against migratory pest infestation. The actions of individual farmers in managing their pest problems could have detrimental effects on the community as a whole. In this regard, pest management could be viewed as a common property problem and dealt with through effective collective action. In Asia, where farms are uniformly small and farmers nearly homogeneous, collective action for pest control seems to be quite an attractive option. Synchronization of planting is the single most important community action strategy in pest management.

Asynchrony is significantly related to the buildup and field-to-field carryover of pest populations. Because synchronous planting can prevent pests from building up and thus can reduce crop damage, it could greatly improve crop yields. The extent of synchrony would be based on the minimum period in which pests can complete one life cycle. Rice fields in a contiguous area have to be planted within three to four weeks to capture the benefits of synchrony (Heinrichs and Mochida 1984).

Several factors may constrain synchronization of planting schedules in a particular location and for particular crops. Loevinsohn (1985, 1987) investigated the causes, extent, and effects of synchronous rice cultivation in Nueva Ecija, Philippines. These included irregularities in water distribution and drainage or variation in the date irrigation water arrived at farms; unavailability of tractor or custom hire work during land preparation; unavailability of labor during transplanting; and no access to credit.

On the whole, treating pests as a common property resource (or a public liability) would entail collective action by constituents and support from the public sector. Recognizing both positive and negative externalities that pest control agents possess, group action could be much more effective than individual action. The challenge to governments is to create an environment that promotes these strategies in ways that achieve growth, equity, and environmental sustainability.

Pesticide Pricing Policies and IPM

As noted previously, even with a well-established IPM program, pesticides may have to be kept as a technology of last resort. Essentially, the idea of pesticide use in IPM is to spray only when it is imperative to do so, using the smallest amount needed to do the job. To make IPM more attractive, pesticides ought not to be subsidized. In fact, farmers will take the trouble to learn and apply IPM techniques only when the cost savings associated with insecticide application make it worth their while. The highly acclaimed IPM training in Indonesia was preceded by a comprehensive reform of pesticide regulation and the removal of all subsidies for rice insecticides (Rola and Pingali 1993). In addition to the removal of subsidies, a sustainable pest management program may warrant the taxation of agrochemicals to account for the social costs associated with indiscriminate pesticide use. Antle and Pingali (1994) have shown that a 100% tax on insecticides for rice could actually have a positive productivity effect associated with improvements in farmers' health resulting from reduced exposure and thereby increased labor productivity. For developed country agriculture, Carlson and Wetzstein (1993) and Zilberman et al. (1991) have argued that pesticide taxation has the potential to eliminate many of the problems associated with pesticide use.

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