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Insect Resistant Rice, Maize and Wheat Cultivars in Sustainable Agriculture

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Abstract

The achievement of self sufficiency in food production is a major objective of governments throughout the world. Insects are one of the major constraints that limit the production of food crops. To mitigate losses due to insects, insect resistant cultivars are sought as a major tactic in the development of integrated pest management strategies. The integration of insect resistant cultivars with other pest management tactics contributes to crop pest management strategies that are environmentally and economically acceptable. Multiple pest resistant crop cultivars have high yield stability when grown in pest-infested environments. Significant progress on a global basis has been achieved in the breeding and commercial utilization of insect resistant rice, maize and wheat cultivars and examples are discussed. Biotechnology tools have been successfully used to overcome some of the breeding constraints that have limited the development of insect resistant crop cultivars and transgenic cultivars are being commercially grown.

I. Introduction

Modern plant breeding techniques have contributed to the dramatic increase in cereal crop yields and production on a world basis. However, in spite of the significant progress achieved, cereal crop productivity gains in many countries have barely kept ahead of population increases. In fact, cereal grain stocks in some countries have deteriorated to the state where widespread famine threatens the stability of governments.

There is a diverse and complex group of constraints that limit food crop production. Among the numerous abiotic and biotic constraints, insect pests are of major importance. Effective pest management programs have been developed to mitigate the importance of insects as production constraints. The foundation of integrated pest management (IPM) programs should be based on the conservation of natural biological control agents and crop cultivars that are not only well adapted to the various abiotic constraints but also have genetic resistance to insect pests and plant diseases. The breeding of cereal crop cultivars that have multiple resistance to pests and tolerance to abiotic stresses is essential if we are going to experience another "Green Revolution," which some have termed the "Super Green Revolution" (Conway *et al.* 1994), or the "Gene Revolution" (Kung 1993).

A major concern in the development and dissemination of high-yielding cereal crop varieties has been genetic vulnerability and genetic erosion. Many of the currently planted modern wheat, maize and rice varieties are genetically uniform. Genetic uniformity of resistance genes in modern Indian wheat varieties was responsible for outbreaks of the shoot fly *Atherigona* spp. and Karnal bunt *Tilletia indica* (Mitra) in the 1970s. More than 67% of the wheat fields in Bangladesh were planted to cultivar "Sonalika" in 1983 and 30% of the Indian wheat fields to the same cultivar in 1984 (Dalrymple 1986). In 1970, more than 15%of the US maize crop was destroyed by the

southern corn leaf blight *Bipolaris maydis* (Nisikado) Shoemaker as a result of the same cytoplasmic genes being used in the breeding of all the major varieties (FAO 1996). In China, all F_1 rice hybrids -covering 15 million hectares- have the same male sterility genes (FAO 1996) and all modern rice varieties share the same dwarfing gene (Hargrove *et al.* 1985). Korea reported impressive rice grain yield increases after releasing varieties with the semidwarf gene such as Tong-il. In 1978, about 76 of the rice area was planted to high yielding varieties (HYVs) with the semidwarf gene but in 1979 a severe blast disease epidemic affected the HYVs more severely than the traditional varieties. As a result, the rice area planted to HYVs decreased and rice production declined (Figure 1) (Rural Development Administration 1985). Broadening of the genetic base is dependent on availability of diverse germplasm. These examples point out the need to broaden the genetic base of major crops when breeding new crop varieties.

Development of crop cultivars having genetic resistance to insects requires an effective program of germplasm conservation, evaluation and utilization. The status of developing insect resistant varieties of the world's three most important cereal crops, rice, wheat and maize, using conventional breeding methods and biotechnology, are herein discussed.

II. Germplasm Conservation

Rice

Rice, *Oryza sativa* L., is cultivated from 530 N to 400 S latitude where it is adapted to a wide range of environmental conditions from waterlogged lowlands to uplands. Rice is the primary staple of more than two billion people in Asia and hundreds of millions of people in Africa and Latin America (IRRI 1985). Among the major food crops rice is the only one that is almost exclusively a human food. Rice provides 80% of the caloric intake

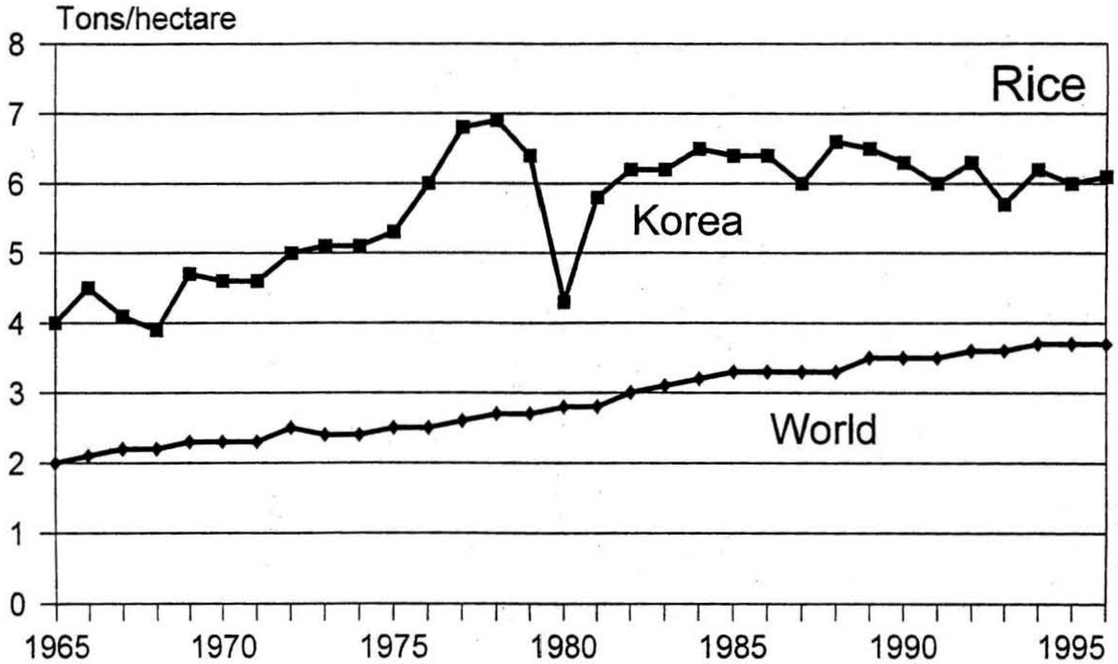

Figure 1. Rice yields in metric tons per hectare in Korea and the world (average of all countries) from 1965 to 1996 (FAOSTAT).

for two billion Asians and one third of the caloric intake of one billion persons in Africa and Latin America (Chang 1984). Robert F. Chandler, IRRI's first Director-General, stated in 1979: "so dependent upon rice are the Asian countries that throughout history a failure of that crop has caused widespread famine and death". Today, rice is just as important to food security, or more so, than it was in 1979.

There are more than 100,000 strains of rice in the world. Utilization of the genetic diversity which exists in rice has been economically profitable resulting in an increase in global rice yields from 2.0 m t/hectare in 1965 to 3.7 m t/hectare in 1996 (Figure 1). Korea, with a very strong breeding program, had average rice yields increasing from 4.0 m t/hectare in 1965 to 6.1 m t/hectare in 1996 (Figure 1). During this same period, rice area has decreased slightly from 1.2 billion hectares to 1.0 billion hectares (Figure 2). The contribution of rice landraces from genebanks in South Asia is estimated at $150 to $200 million per year (FAO 1996). Included in the diversity which exists in the world collection of rice is genetic resistance to numerous rice insect species.

Rice germplasm collections, varying in size from a few hundred to several thousand accessions, are maintained in various countries by national research programs and by International Agricultural Research Centers (IARCs) of the Consultative Group on International Agricultural Research (CGIAR). Estimates are that 95% of landraces and 10% of the wild species have been collected (FAO 1996). The global collection consist of approximately 420,000 accessions including duplicates (Table 1). The largest holdings and the global base collection are at the International Rice Research Institute (IRRI) in the Philippines (19% of the global total). Other large holdings are located in national programs in China, India the U.S. and at the West Africa Rice Development Association (WARDA) in Cte d'Ivoire (FAO 1996). The rice germplasm collection and conservation programs have been successful on a

global basis and have provided a large number of accessions for use in insect resistance breeding programs.

Table 1. The siz largest countries'/CGIAR Centers' holdings of ex situ wheat, rice and maize germplasm collections(FAO, 1996)

Country/Agency	Accessions (no,)	Percent
	Wheat	
CIMMY	101,985	13%
USA	54,915	7%
Russia	47,070	6%
India	47,070	6%
Germany	47,070	6%
Italy	39,225	5%
Others	447,165	57%
Total(world)	**784,500**	
	Rice	
IRRI	79,895	19%
China	54,665	13%
India	50,460	12%
USA	33,640	8%
Japan	21,025	5%
WARDA	16,820	4%
Others	163,995	39%
Total(world)	**420,500**	
	Maize	
Mexico	33,240	12%
India	27,700	10%
USA	27,700	10%
Russia	19,390	7%
CIMMY	13,850	5%
Colombia	11,080	4%
Others	144,040	52%
Total(world)	**277,000**	

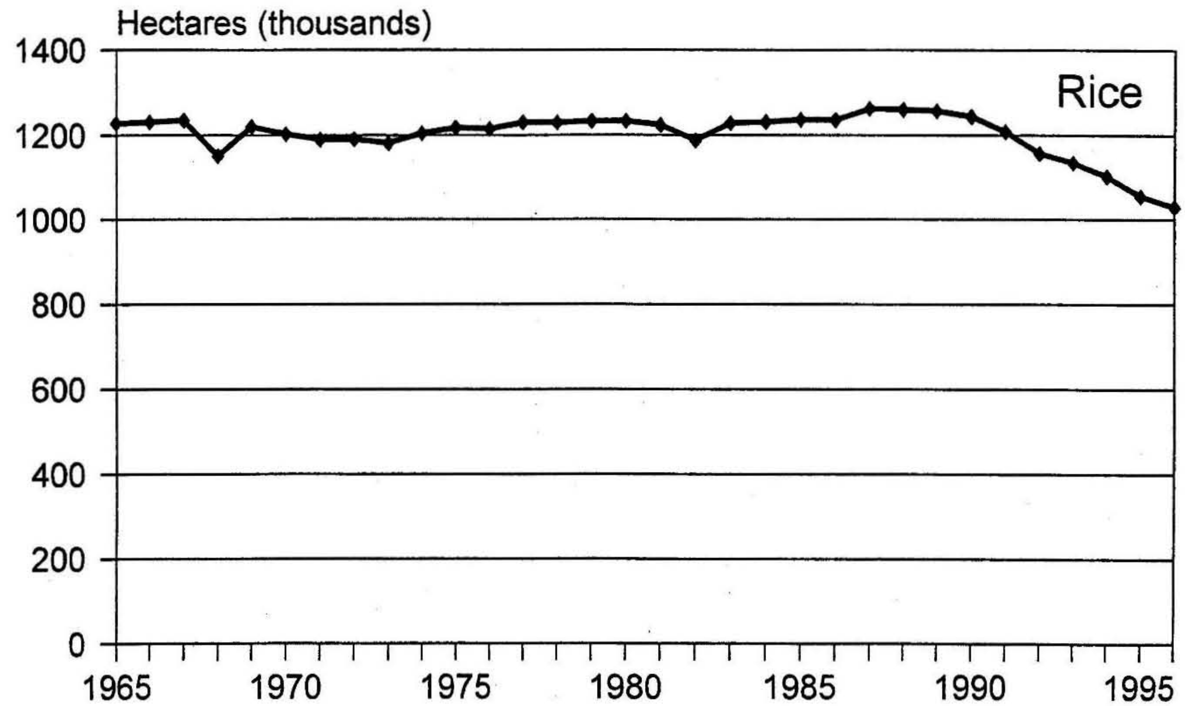

Figure 2. Korean rice area in hectares from 1965 to 1996 (FAOSTAT).

Maize

Maize, *Zea mays* L. is believed to have first been cultivated in Mexico and/ or South America about 7,000 years ago (Mangelsdorf 1974). Maize is grown from northern Asia to the southern cone of South America, from below sea level on the Caspian Plain to over 3,000 meters above in the Andean highlands. (CIMMYT 1992a). Maize is the third most important crop in terms of total production, after wheat and rice and is grown on about 112 million hectares in 134 countries. Globally, yields have increased two-fold from 2.1 m t/hectare to 4.1 m t /hectare from 1965 to 1996 (Figure 3). Korean yields have increased five-fold from 0.9 m t/hectare to 4.1 m t/hectare during this period (Figure 3). However, area planted to maize in Korea has decreased from 49,000 hectares in 1965 to 17,000 hectares in 1996 (Figure 4)

The greatest genetic diversity in maize occurs in the tropical regions of the Americas where many types are grown mostly for human consumption (Foster et al. **in press**). Maize germplasm has been systematically collected and the world collection is estimated to consist of 277,000 accessions (FAO 1996) (Table 1). The largest national collection (27,700 accessions) is maintained by the All India Coordinated Maize Improvement Programme). The largest International Agricultural Research Center (IARC) holding is maintained by the Centro Internacional de Mejoramiento de Maz y Trigo (CIMMYT) in Mexico which consists of more than 13,000 accessions (FAO 1996).

Wheat

Common bread wheat, *Triticum aestivum* L. is considered the most important cereal crop in the world because of the human nourishment it provides and has become the world's major human protein source. Although it is a cool season crop it is grown throughout the widest range of environments of

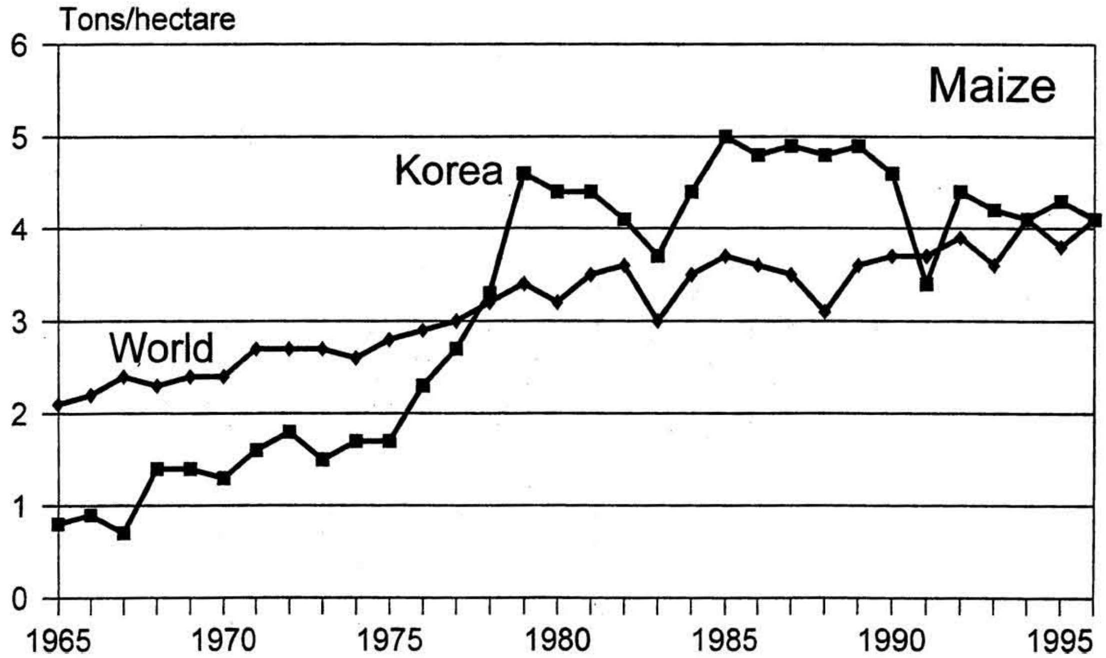

Figure 3. Maize yields in metric tons per hectare in Korea and the world (average of all countries) from 1965 to 1996 (FAOSTAT).

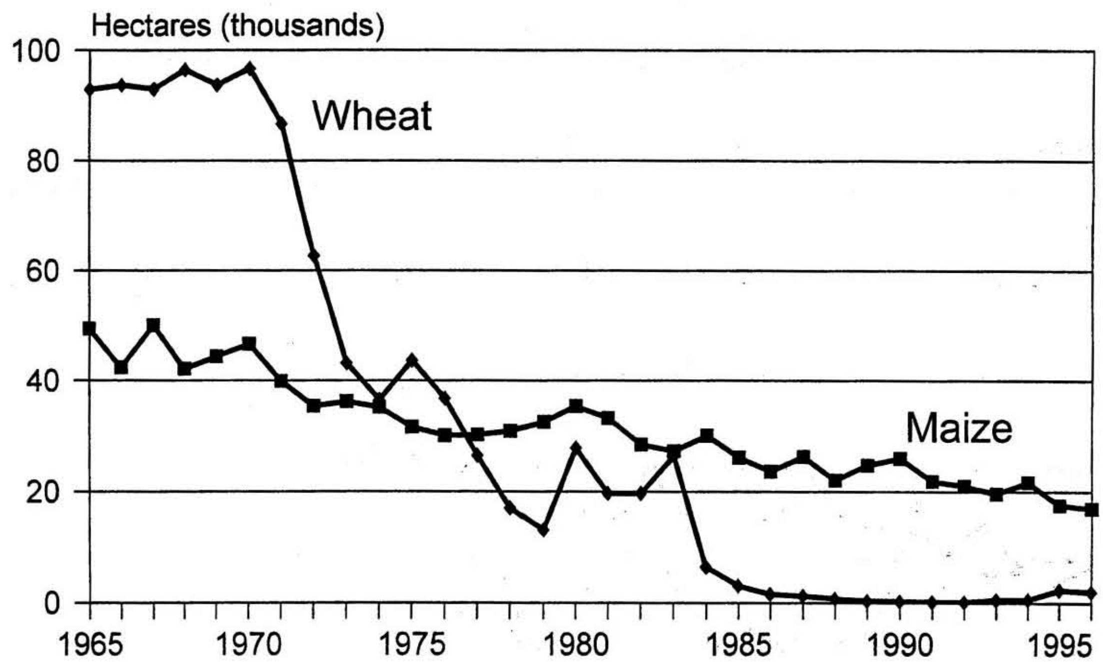

Figure 4. Korean wheat and maize area in hectares from 1965 to 1996 (FAOSTAT).

any cereal crop (Briggle and Curtis 1987). The People's Republic of China is the world's current leading wheat producer with a 1994/95 harvest of 106.4 million metric tons (mmt) while the European Economic Union (82.1 mmt),and the US (63.2 mmt) are second and third respectively. On a continent basis, Asia leads world wheat production at 281.2 mmt followed by Europe (119.9 mmt North America (90.3 mmt). The US is the world's leading wheat exporter (33.1 mmt) while major importers are Japan (6.1 mmt), Egypt and Korea (5.9 mmt each), and Brazil (5.8 mmt) (Anonymous 1996). Globally, wheat yields have doubled, increasing from 1.2 to 2.5 t/hectare since 1961(Figure 5) while in West Europe they tripled, increasing from 2 to 6 t/hectare. Korean yields have increased from 2.0 to 5.0 t/hectare over the same period (Figure 5) However, wheat area in Korea has dramatically decreased from 92,000 hectares in 1965 to only 2,000 hectares in 1996 (Figure 4).

Demand for locally grown wheat has steadily increased in subtropical and tropical developing countries in response to changing food preferences, and urbanization (Klatt 1985). In response, both CIMMYT and ICARDA (International Center for Agricultural Research in Dry Areas), in collaboration with NARS, have successfully utilized the accessions in the germplasm collection to develop material that is adapted to tropical environments.

Wheat accessions in the world's germplasm banks total 784,500 accessions (FAO, 1996) (Table 1). CIMMYT has the largest collection (13% or approximately 100,000 accessions) while the US, Russia, India, Germany and Italy follow in descending order. Only a small number of these accessions have been evaluated for resistance to more than one arthropod pest (Smith *et al.*, in press).

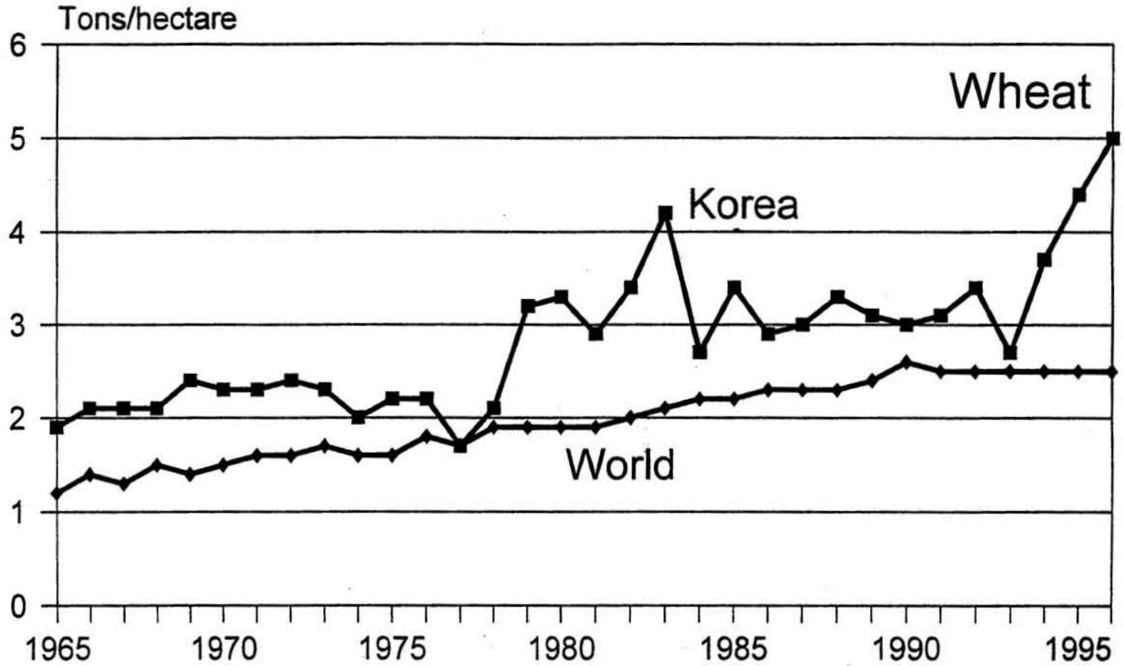

Figure 5. Wheat yields in metric tons per hectare in Korea and the world (average of all countries) from 1965 to 1996 (FAOSTAT).

III. Germplasm Evaluation and Utilization

The progress in breeding for resistance to insects varies among the different crop species and depends on a number of factors including the importance of the crop, importance of pests as constraints to production and the availability of resistant donors to use as parents in the breeding program. Multiple pest resistant cultivars of some crop species are being grown on millions of hectares. Some cultivars have resistance to insects, nematodes and pathogens and tolerance to certain abiotic stresses such as drought or soil mineral toxicity.

Rice

Rice Insects occur in all rice growing environments and cause substantial yield reductions, especially in Asia (Heinrichs 1994b). Although rice insect outbreaks have been recorded over the last 1300 years, they have become more frequent, and the insect complex involved has changed, in the last three decades. Certain insects, such as the leaf- and planthoppers have increased in severity, whereas others, such as certain stem borer species, have declined in importance (Loevinsohn 1994). The increased pest problems accompanying the green revolution have sparked a movement toward an integrated approach to the management of rice insect pests. Insect resistant cultivars have served as a key component in these IPM programs and in the development of sustainable rice production systems.

The status of the screening and breeding for resistance to rice insects in Asia is presented in Table 2. Resistance to 19 insect species has been identified through the screening of germplasm collections and numerous insect resistant rice cultivars are being used as components in pest management systems throughout Asia (Heinrichs 1992). The greater yield stability of multiple resistant cultivars has helped stabilize rice production at

higher levels than previously achieved.

The All India Coordinated Rice Improvement Project (AICRIP) through the screening of rice germplasm at 20 sites has identified sources resistant to seven rice insect species. More than 40 cultivars with multiple resistance to as many as four insect species have been commercially released (Singh *et al.* 1993).

Table 2. Status of screening and breeding for varietal resistance to rice insect pests in Asia (modified from Heinrichs and Quisenberry, in press).

Common name	Scientific name	Screening methods developed	Resistance sources identified	Resistant cultivars released	Genes for resistance identified
Asian rice gall midge	*Orseolia oryzae*	+	+	+	+
Brown planthopper	*Nilaparvata lugens*	+	+	+	+
Whitebacked planthopper	*Sogatella furcifera*	+	+	+	+
Green leafhopper	*Nephotettix virescens*	+	+	+	+
Zigzag leafhopper	*Recilia dorsalis*	+	+	+	+
White leafhopper	*Cofana spectra*	+	+	-	-
Blue leafhopper	*Empoascanara maculifrons*	+	+	-	-
Striped stem borer	*Chilo suppressalis*	+	+	+	-
Yellow stem borer	*Scripophaga incertulas*	+	+	+	-
Whorl maggot	*Hydrellia philippina*	+	+	+	-
Seeding fly	*Atherigona exigus*	+	+	-	-
Armyworm	*Mythimna separata*	+	-	-	-
Thrips	*Stenchaetothrips biformis*	+	+	+	-
Rice bug	*Leptocorisa oratorius*	+	+	-	-
Black bug	*Scotinophara latiuscula*	+	+	+	-
Caseworm	*Nymphula depunctalis*	+	+	-	-
Leaffolder	*Cnaphalocrocis medinalis*	+	+	-	-
Leaffolder	*Marasmia patnalis*	+	+	-	-
Hispa	*Dicladispa armigera*	+	+	-	-

The first hybrid rice developed by Chinese scientists was released in 1976 and by 1991 the area under hybrid rice cultivation reached 17.6 million

hectares (55% of China's total rice area) and contributed to 66% of the country's rice production (Xizhi and Mao 1994). They have 15% yield advantage compared with open pollinated cultivars, possess good grain quality and have multiple disease and insect resistance (Anonymous 1994).

Advances in rice breeding in Korea have been exceptional and Korean rice yields are among the highest in the world. High yielding, multiple pest resistant cultivars have been utilized as a major component in rice IPM programs in Korea (Lee 1992). An example of such a cultivar is Namyeongbyeo which has the desirable agronomic characteristics and is resistant to five diseases, bacterial leaf blight, *Xanthomonas oryzae* (Uyeda and Ishiyama), black-streaked dwarf virus, blast, *Pyricularia oryzae* Cavara, dwarf virus and stripe virus; three insects, *Nilaparvata lugens, Nephotettix cincticeps* (Uhler), and *Laodelphax striatella* (Fallen) and a nematode, *Aphelencoides besseyi* Christie. Namyeongbyeo yields in multi-location trials were 5.69 t/hectare (10% higher than the highest yielding check) and it is adapted to the single-cropping area in the southwestern coastal and southern plain in Korea (Sohn *et al.* 1987).

The IRRI rice improvement program emphasizes the development of germplasm with multiple resistance to key diseases and insects (Khush 1989). Emphasis in screening and breeding activities has been on the major insect pests including the Asian gall midge, brown planthopper, green leafhopper, yellow stem borer *Scirpophaga incertulas* (Walker), and the striped stem borer *Chilo suppressalis* (Walker) (Heinrichs *et al.* 1982). Cultivars with multiple resistance to these pests and the diseases blast, bacterial leaf blight, sheath blight *Rhizoctonia solani* Kuhn, tungro virus (spherical form = ribotungrovirus; bacilliform= badnavirus), and grassy stunt virus (tenuivirus), have been developed (Brar and Khush 1995).

In Asia, where rice is mostly grown under irrigated conditions, modern cultivars have rapidly spread and have had a significant economic and social

impact (Khush 1995). The availability of rice cultivars with multiple resistance to insects and diseases has minimized the need for pesticides and has promoted the adoption of IPM practices. Indonesia's national IPM policy resulted in the banning of 57 rice insecticides (Heinrichs and Adesina, in press). Because of pest resistance, early sprays of insecticides are seldom necessary and pests are maintained at sub-economic level by biological control agents. As a result there has been an upward trend in rice yields and the reduced insecticide use is improving environmental quality and human health of the farming community (Khush 1995).

Maize

Maize is cultivated in a multitude of ecologically diverse niches, exposing it to many biotic and abiotic stresses Among the important biotic stresses are the insects and diseases. The number-one insect enemy of maize farmers in the tropics is the stem borer group. Feeding by these insects on maize leaves, tassels, stems, and ears results in stunted, broken, unproductive plants riddled with borer holes and tunnels. In developed countries, borer damage is mitigated through integrated pest management practices including insecticide use. Farmers in tropical developing countries have limited access to similar controls and may lose a third or more of their harvest to borers, armyworms and the corn earworm *Helicoverpa zea* (Boddie) (CIMMYT 1992a). The development of maize IPM programs for the tropics requires the breeding of insect and disease resistant varieties as a major tactic in insect management.

Both CIMMYT, in Mexico and IITA in Nigeria, are developing tropical maize varieties with resistance to borers. The IITA program has developed three maize populations with moderate resistance to *Eldana saccharina* (Walker) and two populations with moderate resistance to *Sesamia calamistis* Hampson. These populations are intended as sources of resistance to be used by NARS breeding programs, and not as final products for release to farmers

by IITA (N. Bosque-Perez, IITA, pers. comm.).

The CIMMYT program has been successful in developing sources of insect resistance to single and multiple pest species and these sources are provided to the NARS for further development to fit local conditions, and for commercialization (CIMMYT 1992b). A multiple insect resistant tropical (MIRT) population 390 was developed for the lowland tropics and has have high levels of resistance to the major tropical borers and armyworms and to maize streak virus, a major pathogen of maize in Africa (Mihm 1985). Sources identified as resistant to insects at CIMMYT have also been utilized in the USA. A population from Antigua Group 2 was used to develop resistance to the southwestern corn borer *Diatraea grandiosella* (Dyar). Several lines and one population with resistance to *D. grandiosella* and the fall armyworm *Spodoptera frujiperda* (J. E. Smith) have been released to the public. Some inbred lines from the Mississippi, USA program are highly resistant to *Chilo partellus* (Swinhoe) an African stem borer while other lines are resistant to the Asian corn borer, *Ostrinia furnacalis* (Guene). Because these sources possess multiple insect resistance they can be incorporated into hybrids and varieties for use by farmers around the world (Davis et al. 1988).

In spite of the progress achieved in breeding borer resistant maize cultivars, area planted to such cultivars is still limited as satisfactory insect resistant maize cultivars have not been made available to farmers (Hess 1997). This is partially due to the lack of high levels of borer resistance. Biotechnology approaches to breeding hold promise of raising the level of resistance and thus accelerating the commercialization of maize cultivars.

Wheat

The major insect pests of wheat in the tropics and subtropics are the wheat stem sawflies, Hessian fly, Sunn pests and aphids (Miller 1992).

Disease and insect resistance have been as important as yield potential in determining the impact of wheat germplasm in the developing world (CIMMYT 1992b). Insect resistance is a major objective of the CIMMYT and ICARDA wheat breeding programs. Historically, CIMMYT has given significantly less emphasis to breeding for insect resistance in wheat than its sister institute, ICARDA, because the major wheat pests, the Hessian fly, *Mayetiola destructor* (Say), and the wheat stem sawflies are found in West Asia and North Africa which are in ICARDA's mandate zones. However, with the increasing pest status of the Russian wheat aphid, *Diuraphis noxia* (Mordvilko) in South Africa and its movement from Asia Minor into the Americas, Mediterranean countries, Middle East, and Ethiopia both CIMMYT and ICARDA are breeding for insect resistance in wheat in collaboration with NARS. The use of resistant varieties of wheat will form the keystone of some of the pest management programs in the Mediterranean region because of their low cost to farmers. The wheat stem sawfly, Hessian fly, and aphids are the insects with the greatest potential for control by the strategic release of resistant germplasm (Miller 1992).

Cephus pygmaeus L. is the most important wheat stem sawfly species in the Middle East. In Morocco, wheat stem sawfly compounds the damage done by the Hessian fly resulting in 100% losses on some farms. The ICARDA bread wheat and durum wheat breeding programs are incorporating the solid stem characteristic for sawfly resistance into improved genotypes suitable to the West Asia and North Africa (WANA) region. One bread wheat line possessing both wheat stem sawfly and Hessian fly resistance has been released for use by farmers (Miller 1992).

The sawfly *Cephus cinctus* Norton is a major pest of wheat in the northern Great Plains of North America and in Canada (Weiss and Morrill 1992). In 1989 this pest reduced wheat yields by 80% in the state of Montana, USA. Currently grown spring wheats with sawfly resistance, have

medium to high yields, good baking quality and disease resistance (Smith *et al.*, in press).

The Hessian fly *Mayetiola destructor* (Say) is a major pest of wheat throughout the most of the world's wheat production areas of North America, Europe, North Africa, and Russia (El Bouhssini *et al.* 1988, Everson and Gallun 1980). In the USA, feeding of the larvae between the leaf sheath and the stem causes about US$ 100 million per year (Smith *et al.* in press).

Screening for resistance to the Hessian fly in the tropics is conducted by the Moroccan national program (El Bouhssini *et al.* 1992). In 1989 the first bread wheat carrying the H5 gene was deployed in Morocco. Because the Moroccan Hessian fly appears to be more virulent than the Hessian fly in the US, more durable sources of resistance, such as that from wild species of *Triticum,* must be exploited.

Twenty seven genes for Hessian fly resistance have been identified in common wheat, *T. aestivum* in North America. Between 1950 and 1983, 60 Hessian fly resistant cultivars were released and by 1984 more than 10 million ha of Hessian fly resistant wheats were grown in 30 US states. About 70% of the cultivars currently grown in the US are resistant to the Hessian fly and this resistance has been estimated to be worth about US$ 60 million in reduced losses (Smith *et al.*, in press).

The Russian wheat aphid, *Diuraphis noxia* (Mordvilko) is a major wheat pest in Mexico, South Africa, and Lesotho. It has recently immigrated to the Great Plains of North America where it is a severe pest (Smith et al , in press). A single feeding can kill a tiller and leaves attacked by as few as one aphid show yellow striping and curling within 24 hours. Estimated losses in small plot studies in Ethiopia were 60% in some regions (Miller 1992). Losses in the US from 1986 to 1993 were estimated to be US$ 850 million (Legg and Amosson 1993).

Studies have indicated that sources of resistance from lines originating from the geographic origins of the aphid are most promising. Thus, the ICARDA screening program is concentrating on landraces, wild relatives and advanced lines originating within West Asia and North Africa.

CIMMYT entomologists have screened several thousand spring wheats, triticales, ryes, and barleys for resistance. Only a small number of resistant sources among the wheats have been found. Thus, alien sources, involving both close and distant relatives, such as *Triticum dicoccum* Schrank and wild wheats are being evaluated (M. van Ginkel, CIMMYT, pers. comm.). In the bread wheat program CIMMYT breeders are using sources of resistance from Turkey, Eastern Europe, Russia, Iran, Afghanistan, Tunisia, South Africa and the USA. Russian wheat aphid resistant wheat cultivars were first commercially grown by farmers in the US and the South African Free State Province in 1996 (Smith *et al.*, in press).

IV. Biotechnology as a Tool to Enhance Resistance

Several biotechnological approaches are employed in the development of insect resistant rice cultivars. Tissue and anther culture techniques are utilized to increase the level of resistance, and wide hybridization and transformation contribute to the generation of novel genetic variation by increasing the gene pool available to breeders. Biotechnology holds promise as a useful tool in the development of multiple insect resistant rice varieties. IRRI scientists in cooperation with the Rockefeller Foundation Biotechnology Network are incorporating novel genes for resistance into rice through transformation (Potrykus *et al.* 1995). Novel genes such as the *Bt* (*Bacillus thuringiensis*) gene coding for toxic proteins, inhibitors of digestive enzymes such as protease inhibitors and ribosome inactivating genes are being transferred to rice.

Wide Crosses

Where screening of the rice germplasm collection has failed to identify adequate levels of resistance to certain rice insects, wild species have provided resistance sources (Heinrichs et al. 1985, Medina et al. 1986, Wu 1986). Although wild species are often incompatible with *O. sativa* in conventional breeding, they can be used as donor parents using wide hybridization and embryo rescue techniques (Heinrichs 1992). In studies at IRRI, genes from seven wild rice species have been transferred to *O. sativa* for resistance to the brown planthopper *Nilaparvata lugens* (Stl), whitebacked planthopper *Sogatella furcifera* (Horvath), and the yellow stem borer *Scirpophaga incertulas* (Walker).

Transgenic Plants

Rice

The transgenic approach to enhancing resistance to rice insects is attractive because it provides access to non-rice genes, allows purified rice genes to be returned to rice after modifications that give enhanced performance not attainable through mutation and recombination in vivo, and allows the addition of specific characters into rice without the linkage drag and the requirement for backcrossing that accompany sexual hybridization (Bennett et al. 1997). Scientists at IRRI and at other locations linked by the Rockefeller Foundation Biotechnology Network are incorporating novel genes for resistance into rice through transformation. The genes include the *Bacillus thuringiensis* Berliner (*Bt*) genes cryIA(b) and cryIA under the control of various promoters and several proteinase inhibitor genes. The rice insects controlled by these genes include the yellow stem borer (Potrykus *et al.* 1995), striped stem borer (Bennett et al. 1997) and the leaffolder *Cnaphalocrocis medinalis* (Guene) (Fujimoto *et al.* 1993).

Genetic engineering of rice with toxin genes from *Bt* has the potential to

provide effective and environmentally safe control of several rice insect pests. Of major concern, however, is its potential lack of stability (Bottrell *et al.* 1992). Numerous strategies have been proposed to delay the evolution of rice pest resistance to *Bt* toxins in transgenic rice plants (Bottrell *et al.* 1992, Cohen *et al.* 1996) One strategy is the use of spatial refuges in association with the combination of multiple *Bt* toxins that bind to different receptors. Proposed spatial refuges consist of tissue specific expression, within field mixtures of *Bt* and non-*Bt* rice plants, and field-to-field mixtures of *Bt* and non-*Bt* rice. Cohen *et al.* (1996) reported that the genetic engineering of rice is progressing rapidly and *Bt* genes may soon be in agronomic backgrounds suitable for use by farmers. They caution that genetic engineering is proceeding at a faster pace than the development of resistance management strategies.

Maize

Maize, the most important commercial seed species, is considered the "Holy Grail" of crop genetic engineering because it potentially offers enormous financial rewards to the global seed industry. In the USA and Western Europe farmers spend US$ 350 million annually for insecticides that are only 50% effective against the European corn borer *Ostrinia nubilalis* (Hbner) (RAFI 1991). In the USA the European corn borer, is estimated to cause US$ 1 billion in maize crop losses annually. (Losses in the state of Nebraska, USA are US$ 48 million. Losses are about 10% per borer per stalk and populations of 3 borers per stalk are common (Bullock and Sollod 1996). Larval feeding reduces yields by damaging the plant's vascular system which reduces the flow of minerals, sugars and starches in the stalk. About 3 million hectares of maize in the US are annually treated with insecticides to control this pest (Bullock and Sollod 1996).

Transgenic hybrids with the *Bt* genes, which encode insect-specific toxic

proteins in maize (Koziel et al. 1993) have been field tested and are now being marketed in the US for protection against *O . nubilalis* (Foster et al. **in press**). 1996).Two types of technology have been developed. The Monsanto technology provides season-long, throughout the plant technology while the Mycogen/Ciba technology does not last the entire season and the expression is limited to the green tissue. Results from field tests conducted in 1994 indicated that *Bt* hybrids had a 890 kg/hectare increase (10%)as compared to conventional hybrids without the *Bt* gene (Bullock and Sollod 1996).

Hybrid maize seed with the *Bt* gene was first commercially sold to growers in 1996 by Ciba Seeds and Mycogen. Monsanto's "YieldGard" *Bt* maize technology was provided commercially to growers in 1997 through seed companies such as Pioneer, DeKalb and Northrup-King. About three million acres were planted to YieldGard in 1997. Mycogen began selling its *Bt* hybrids under the name of "NatureGard.." in 1996. NatureGard hybrids have both the *Bt* gene and native resistance genes in the same plant (Bullock and Sollod 1996). In the US cornbelt about 5% of the area was planted to *Bt* maize seed in 1997 and it is projected that area planted to *Bt* seeds will increase to 25% in the 1998 season.

The next breakthrough expected in the use of *Bt* genes in the management of maize insects in the USA involves the corn rootworm complex consisting of the western corn rootworm *Diabrotica virgifera virgifera* LeConte, and the northern corn rootworm *D. barberi* Smith and Lawrence (Coleoptera: Chrysomelidae). Economically, the corn rootworm complex poses the most important insect problem in maize in the USA cornbelt. Crop losses due to rootworm damage and cost of insecticidal control annually amount to millions of dollars (Meinke *et al.* 1997).

Corn rootworm larvae damage the plants by feeding on the roots. Extensive feeding weakens root systems and injured plants cannot take up

water and nutrients and the plants are susceptible to lodging. Corn rootworm management involves crop rotation and insecticide applications to control adults or larvae (Pike *et al.* 1995). Crop rotations, generally, are not practical and the major rootworm species, *D. virgifera virgifera,* is developing resistance to insecticides (Meinke *et al.* 1997). Because of the economic importance of developing new management strategies there is a great deal of commercial interest in developing *Bt* transgenic maize hybrids for rootworm control and seed companies are expected to release commercial *Bt* varieties for rootworm control in the next five years (J. E. Foster, personal communication).

V. Conclusions

A global pursuit food self-sufficiency has been underway since the 1960s. With the widespread cultivation of the modern rice, maize and wheat cultivars there has been a temporary respite, in some countries, in the race to prevent hunger, as cereal production has more than doubled, outracing the 80% leap in the world's population.

Taking rice as an example of future food crop production requirements, it has been stated that population growth, in rice growing countries, is so intense, that 80 to 100 million additional people must be fed each year (IRRI 1990). Resource-poor farmers are being forced to till highly erodible and marginal land. These less favorable areas now produce only 25% of the world's rice, but within the next two decades, they must sustain hundreds of millions of farmers who have yet to realize the benefits of new technology.

Agricultural scientists face a tremendous challenge to develop technology, that will increase the productivity of existing land resources, and simultaneously maintain soil fertility, and to develop crop pest management

strategies that are environmentally and economically acceptable. Plant resistance is a principal component and plays a vital role in integrated pest management systems in many crops (Heinrichs 1994a). It serves as a foundation stone on which pest management programs are established. Both conventional plant breeding and biotechnology methods will contribute to improved crop protection technology of future rice, maize and wheat cultivars.

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지속적 농업을 위한 해충저항성 벼, 옥수수, 및 밀 품종 개발

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초 록

식량 자급자족은 세계 각국 정부의 공통적인 주요 목표이다. 해충은 식량생산을 감소시키는 주요 제한 요소이다. 해충에 의한 손실을 감소시키기 위한 해충저항성 품종의 활용은 해충의 종합적 방제 전략의 중요한 수단으로 대두대고 있다. 해충저항성 품종을 포함하는 해충의 종합적 방제 전략은 친환경적이며 또한 경제적인 것으로 받아들여지고 있다. 여러 해충에 대하여 저항성을 나타내는 복합작인 저항성 품종은 해충 피해지역에 재배하여도 안정적인 생산을 나타낸다.

세계적으로 작물의 해충저항성 품종들이 성공적으로 육종, 개발되어서 상업적으로 이용되고 있는 예가 많으며 그 성공사례에 대하여 논하고자 한다. 아울러 이러한 해충저항성 품종을 육종하는데 있어 제한적인 요소들을 극복할 수 있는 수단으로 생물공학적인 기법들이 성공적으로 사용되고 있으며, 그렇게해서 개발된 형질전환된 해충저항성 품종들이 지금 상업적으로 재배되고 있다.

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