PART III. Selected Management Practices for Rice Diseases

Section 4. Utilizing Genetic Diversity

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1. Historical perspective

In general, diversity in crop production refers to two things (IBPGR 1991). First is the diversity of crops in a single field at one time or at a different time sequence with or without a defined pattern of arrangement. Both have been seen in traditional agriculture for subsistence farming. In modern agriculture, over time, this has evolved to crop rotation, or specially designed spatial arrangements as demonstrated in the interplanting of glutinous and hybrid rice which will be discussed below. Second is the diversity in genotype of a single crop species planted in the same field at a given time. The use of genetic diversity to control plant diseases by mixed planting of different cultivars or blending isogenic lines of multiline varieties has been found to produce remarkable results (Wolfe 1985). This is the emphasis of this section to shed lights on its merit on modern agriculture.

Traditional agriculture systems were based on crop varieties and landraces that were genetically heterogeneous as a result of natural and, sometimes, human selections (Brush et al 1992, Bellon 1996). Diversity was common in crop species and even in one species in single fields. As human demands for food and fiber production increased, the diversity of different crop species in single fields has been realized not to yield the desired level. Diversity has gradually decreased to give way to single-crop species with high yield potential. In rice, for instance, modern agricultural development has transformed the diverse, traditional production system with different landraces into a monoculture system that relies only on a few fertilizer-responsive and high-yielding varieties. This occurred particularly through the use of a single source, the dwarfing gene from Dee-Geo-woo-gen, which narrowed greatly the genetic variability leading to genetic uniformity (Khush 1977).

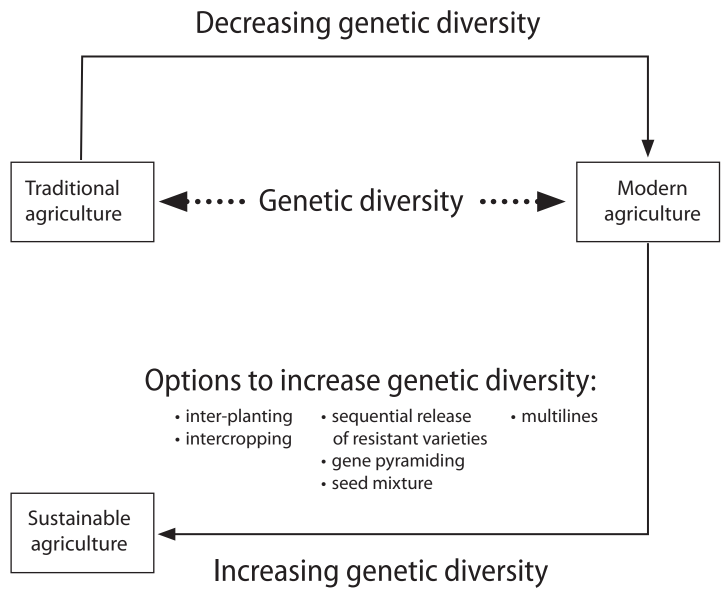
In resistance breeding, single resistance genes may have been widely and frequently used by different rice varietal improvement programs. Thus, even with built-in resistance, genetic uniformity of rice varieties and resistance to important diseases has become a general scenario in rice fields. Inevitably, this production system enhances the vulnerability of the rice crop to disease epidemics. Historical records show that, under certain circumstances, these epidemics have led to serious yield losses and reduced the longevity of many resistance genes (Ou 1985). In Japan, rice production has been a monoculture system longer than in tropical Asia. Kiyosawa (1982**)** estimated that the effective life of a resistance gene to *Magnaporthe oryzae*, the rice blast pathogen is, on an average, 3 years. This seems to be true in resistant rice varieties grown in similar production environments across the different rice growing countries in Asia.

In a monoculture system, genetic uniformity creates genetic vulnerability. This system suits large-scale production requirements, which is a primary consideration in a crop production system. However, there may be different varieties grown in fields of rice-bowl regions across the rice-growing countries, but most of these varieties likely carry the same resistance genes against the same pathogens. Genetic diversity among these cultivated varieties is, therefore, narrow and reduced. The system is vulnerable to more insect pest and disease outbreaks. In the 1970s and 1980s, the frequent tungro epidemics in the Philippines and Indonesia were associated with a rice monoculture system where there were only a few rice varieties with a similar genetic background for resistance to the viruses and the insect vector of rice tungro (Mew 1991). In 1970 in the USA, when an epidemic of southern corn leaf blight caused by the fungal pathogen *Helminthosporium maydis* struck the U.S. Corn Belt, the yield of corn production lost by an average of 15% with some at 50% or higher in individual fields or states. This epidemic prompted the U.S. National Academy of Sciences to organize a Committee on Genetic Vulnerability of Major Crops to examine the situation (NAS 1972). The committee concluded that the southern corn leaf blight epidemic was due to a new strain (race T) of the fungal pathogen that adapted to the single source of germplasm (Texas cytoplasmic male sterile [Tcms] corn) utilized in developing the hybrid corn planted over a large area. The key finding of the committee was that the genetic uniformity was the basis of vulnerability to epidemics. The committee also concluded that most major crops were genetically uniform, therefore, highly vulnerable to some disease epidemics.

More than half a century since this NAS report, has the situation changed or improved? Most likely, the situation has not changed much, even in the USA and other countries. Of course, new strategies of disease management have been developed and implemented, some of which appear to complement genetic vulnerability while the crop continues to be genetically uniform. Broadening the genetic basis of resistance breeding and increasing genetic diversity through crop cultivation require the collective attention of plant pathologists and plant breeders.

Despite this concern for genetic uniformity and vulnerability, host plant resistance (HPR) is an important tool for rice disease management, especially in less developed tropical countries. Other management strategies have been developed and put in place where needed, most of which are neither readily available nor affordable to farmers in developing countries, besides introducing environmental concerns. For example, there are regional differences in using chemicals. The use of chemicals for control is more common in the temperate region of East Asia than in the tropical countries of Southeast Asia. In rice, HPR has played, and will continue to play, a key role in sustaining the productivity of modern semidwarf, high-yielding rice varieties. To achieve the needed productivity, it is not possible to advise farmers to go back to planting diverse traditional varieties or landraces that yield less. As a progressive strategy, the best option is to design a production system that takes into account disease management methods that not only can sustain the productivity but can also maintain adequate genetic diversity and resilience. Managing genetic diversity is, therefore, an integral component of this system.

A target pathogen can continue to evolve and readjust its population to adapt to a new environment of host resistance and changing cropping systems. Maintaining crop health requires anticipatory and proactive strategies. Genetic diversity appears to be a better option especially for high-epidemic diseases such as blast. Leung et al (2003) indicated that genetic diversity is like the "currency" to manage the "arms race" between the pathogen and the host genotype. Breeding efforts spanning 7 to 8 years were needed to "fix" and then to introduce a new genotype to farmers for commercial production (**GD Figure 1**). Currently, improving genetic diversity of crop plants has been focused on cereals. There are two common approaches to improve genetic diversity: resistance breeding and resistance deployment. In resistance breeding, broad-spectrum resistance for major and minor diseases is important. With the completion of the rice genomic sequence, scientists now have the capacity to identify a large pool of resistance and defense—related genes that encode multiple mechanisms of resistance. Functional genomics provides knowledge to understand how these genes work for effective use in resistance breeding against diverse



GD Fig. 1. Roles of genetic diversity in modern agriculture and options to increase genetic diversity in achieving sustainability. Source: Leung et al (2003).

rice diseases, especially blast, bacterial blight, tungro, or sheath blight (**see respective chapters/sections in Part II**).

In resistance deployment at the crop and cropping system level, the need is to go beyond the deployment of diverse resistance genes but also to using a large suite of agronomic traits that together can provide enhanced resilience to a wide range of biotic or abiotic stresses. Two common methods have been used to improve genetic diversity through resistance deployment: multiline and cultivar mixtures. Multiline involves mixing isogenic lines with different resistance genes to increase genetic diversity among crop varieties. Reviews on the subjects include Browning and Fry (1969), Wolfe (1985), Smithson and Lenne (1996), and Mundt (2002). The idea of the multiline was initiated with the development multiline oats (*Avena sativa*) cultivars (Wolfe 1985). The mixtures of genotypes were selected for phenotypic uniformity and genetic diversity for other traits, e.g., disease resistance. The multiline hypothesis influenced Browning and Fry (1969) and maybe Borlaug (1959) who considered genotypic difference in disease resistance genes against stem rust of wheat caused by *Puccinia graminis* f.sp. *tritici*. Borlaug (1959) aimed at a "clean crop" in which only the resistant components were exposed in the field, while Browning and Fry (1969) were concerned with the development of a "dirty crop" multiline variety. The "dirty crop" multiline aimed at stabilizing the pathogen population. Both aimed to emphasize the heterogeneity of the crop thus to stabilize the selection pressure on the pathogen. They utilized a backcross approach to produce multiline varieties of oats (Browning and Fry 1969) and wheat (Borlaug 1959) that contained various genes for race-specific resistance to the rust pathogen (*Puccinia* spp.).

Diversity can be achieved by more than one way of planting. To control rust and powdery mildew in wheat and barley, Wolfe (1985) and Mundt (1994), respectively, used a seed mixture of different cultivars. In rice interplanting, a spatial planting arrangement in the same field has been proven to be effective in blast control in Yunnan, China (Zhu et al 2000). There is a concern that interplanting of two or more varieties in the same field can hamper the mechanization of rice production. In a large-scale system for rice crop production (both planting and harvesting), machinery can be designed to match the need. Crop production is dynamic. The need drives the design and the products of the design push the pattern of production tool use in a system.

2. Definition of the terms

Definition of a few common terms and clarification on the practice of mixtures, especially in relation to rice, are necessary on the subject of genetic diversity.

Monoculture refers to the "continuous use of limited varieties of a single crop species over a large area." However, in real situations, varieties of a crop species may change in space and in time. Likewise, in dealing with plant disease problems, the resistance gene among varieties (genotypes) of the crop is emphasized and it may vary over time in a spatial scale. In a plant pathologist's view on monoculture, it has a narrow sense to mean a single-crop variety with certain resistance genes deployed over a wide geographical scale. This is how "monoculture" is used here. In such a context, there may be a situation where different varieties possess the same resistance gene(s) against a specific pathogen such as the blast or bacterial blight pathogen. This is a system of rice production seen in many rice growing countries. There are few studies on disease spread or pathogen dispersal and on disease epidemic process in production systems of crop diversity. There are relatively more studies on the influence of genetic diversity of the same crop species. This appears to be adapted by NAS (1972) in the report of southern corn leaf blight. This is also the definition of "monoculture" used by Zhu et al (2000) in their well-publicized paper.

Genetic diversity is, therefore, taken to mean diverse resistance genes to a particular pathogen among varieties of a single crop species. Genetic diversity may also mean the incorporation of different resistance genes in a single variety. Variety or cultivar diversity also means to grow together in a field two or more distinct varieties that may carry different resistance genes.

For genetic diversification, the interest is towards variety or cultivar mixtures differing in resistance genes as it allows genetic diversity and as a means of conserving landraces (Leung et al 2003, Zhu et al 2003). Instead of altering landraces through breeding, a more desirable approach is to conserve existing landraces by actively using them side by side with modern improved genotypes in actual crop production. This is a form of *in situ* conservation of genetic resources as demonstrated in the case of the Yunnan study (Leung et al 2003, Zhu et al 2003). Landraces serve as genetic resources in breeding high-yielding varieties, and are also valued for their unique attributes of high eating quality.

A multiline or cultivar mixture is crop production practiced in a field by interplanting two or more components or using a seed mixture for directly growing a crop. In the cases of oats, barley, or wheat, seed of different lines or cultivars bred for phenotypic uniformity of agronomic traits are mixed together for planting either as a multiline cultivar or a cultivar mixture (mixtures of agronomically compatible cultivars with no additional breeding for phenotypic uniformity) (Browning and Frey 1969, Wolfe 1985). In Japan, seed mixtures of different lines are used for raising a crop presumably because the isogenic lines are phenotypically similar in agronomic characters. In the large-scale experiment on genetic diversity in Yunnan, China, component cultivars were interplanted to achieve genetic diversity. The seed were never mixed during planting as farmers rejected the seed mixture option because rice is usually commercialized as an individual variety. Even though this may not always be the case, it is necessary to ensure consumer preference for grain shape and size in addition to eating quality. In a harvest from seed mixtures of wheat cultivars, this has rarely been a problem because it is made into flour where changes in product cannot be easily detected by consumers. Marketing of grains harvested from rice seed mixtures can be more difficult because variations in grain appearance and differences in eating quality and, sometimes, grain appearance are more discernible. The expectation of consumers is that rice as a market product must be "pure" or "uniform" in appearance when labeled for a certain type of cultivar. If a "mixture" of two or more distinct grain types is detected visually, its market value may decrease.

3. Rice mixtures for controlling diseases

Mixed plantings are commonly practiced in traditional rice cultivation. In rice production for subsistence farming, mixed plantings were also observed (**GD Figure 2**). When production was "modernized," the use of a single rice variety in a single rice field was considered "progressive." During the late 1970s, in central and northern (Banaue rice terraces) Luzon in the Philippines, fields were planted with single semidwarf varieties. Uniform crops stood in most irrigated fields. In the rice terraces, a variety within a single field became more genotypically and phenotypically diverse (Vera Cruz et al 1992). Tall, traditional rice varieties with mixed stands of different phenotypes were observed. Under upland conditions where rice production was subsistent, mixed plantings of rice varieties in the same fields were commonly practiced (Bonman et al 1986). Since the 1970s, intentional planting of two or more varieties in a single rice field was rare if observed at all in lowland paddy fields.

GD Fig. 2. Mixed planting in rice production.

However, the effect against diseases of mixed planting of two or more rice varieties has been reported in different Asian countries. In India, mixed planting of two varieties in alternate rows significantly reduced the damage caused by *Helminthosporium oryzae*, the pathogen causing brown spot (Grümmer and Roy 1966). Varietal seed mixtures resulted in a lower infection rate by *Pyricularia oryzae* than pure stands (Chin and Husin 1982). The population density of brown planthopper and rice grain yield were affected by planting a mixture of susceptible and resistant rice varieties (**GD Table 1**). Mixing of two resistant varieties greatly reduced the hopper population to 26% of the expected density, and increased grain yield by 25% when compared with the values from pure-stand measurements (Pathak and Khush 1977).

Considerable effort has been devoted to developing rice multiline varieties with different resistance genes against rice blast in Japan (Koizumi 2001 and in Taiwan in the 1970-80s (Chiu and Teng 1975). In Japan, attempts to use popular rice varieties, such as Sasanishiki, Nipponbare, and Toyonishiki as recurrent parents to develop multilines against rice blast, have been made since the 1990s.

Sasanishiki, a leading commercial rice variety, was used as the recurrent parent to develop the first registered multiline variety, Sasanishiki BL, released in 1995 (Matsunaga

GD Table 1. Brown planthopper populations and grain yield in field plots planted with mixtures of resistant and susceptible rice varieties. Recomputed by Chang and Oka (1987) from Pathak and Khush (1977).

	% plants		Hoppers/hills	Grain yield
IR1917	IR34	IR36	(85 days)[a]	kg/ha
100	0	0	967	736
0	100	0	37	2,671
0	0	100	15	2,356
33	33	33	41	2,256
	Expected[b]		340	1,921
60	20	20	152	1,816
	Expected[b]		590	1,447

[a]No. of days after transplanting.

[b]Expected from the values for pure stands.

1996). Sasanishiki possessed *Pia* that confers complete resistance to blast but with a low level of partial resistance. Nipponbare and Toyonishiki were used as the recurrent parents to develop near-isogenic lines (NILs). The mixtures of these NILs were effective in suppressing blast development but these had not been registered and released as multiline varieties to the farmers until 2001 (Shindo and Horino 1989, Koizumi and Fuji 1994, Koizumi 2001). Other NILs had been developed and most of their recurrent parents were leading commercial rice varieties with low levels of partial resistance to blast, although all possessed desirable eating quality highly demanded by consumers (**GD Table 2**). To be durable, Koizumi (2001) emphasized the importance of partial resistance of the recurrent parents in multiline development, in addition to major genes.

Extensive research was conducted in Taiwan in the 1970s not only to develop multiline varieties but also to test cultivar mixtures in controlling rice blast (Chiu et al 1972, Chiu and Teng 1975, 1976). During 1971-73, tests on various combinations, including equal proportions of advanced lines of the F_3 and F_4 generations, showed increased yield and reduced blast infection as follows: line mixture > cultivar mixtures > pure stands of varieties (Chang and Wu 1976, Chang and Chao 1977) (**GD Tables 3** and **4**). In addition, there were no significant differences between japonica and indica varieties. Grain yields of mixtures were determined by the yield capacity of the component varieties in the mixture. Thus, good and quality components produced better results in grain yield and disease suppression.

Another multiline variety was developed using Tainan 5 and Chianung 8 as the recurrent parents (Chiu and Teng 1975). Higher levels of resistance to both leaf and panicle blast and better grain yield than those from pure-stands of the parental varieties were demonstrated (**GD Table 5**). The susceptible parental variety was severely infected by blast in the field in the same test. Grain quality was better in the multiline than in the pure stand. However, the multiline variety was never released to the farmers.

3.1. Issues on rice cultivar mixtures

When farmers save mixed seeds for the next planting, the composition may vary since the last crop, as a result of competitive interaction among components and selection due to environmental stress and the pathogen. For example, interplanting of resistant and susceptible rice varieties for tungro management proved that a 1:1 seed mixture was more effective than interplanting of two varieties (I.R. Choi, pers. comm.). However, when farmers saved the seed for planting the next crop, the ratio would not likely be the same.

GD Table 2. Near-isogenic lines used to control rice blast with multilines in Japan. Source: Koizumi (2001).

Recurrent parent	Complete resistance genotype RP	Resistance genes introduced into NILs	Breeding locations	Year released (developed)
Sasanishiki	*Pia*	*Pik-s, Pii, Pik-m, Piz, Piz-t, Pita-2, Pib*	Miyagi Prefecture	1995
Hitomebore	*Pii*	*Pik, Pik-m, Piz, Piz-t, Pib, Pita, Pita-2*	Myagi Prefecture	
Manamusume	*Pii*	*Pik, Pik-m, Piz-t, Pib, Pita,*	Miyagi Prefecture	
Nipponbare	*Pik-s/Pia*	*Pii, Pik, Piz, Piz-t, Pita-2, Pib*	Natl. Agric. Res. Cen	1984
Hokkai 241		*Piz, Pib, Pita-2, Piz-t,Pit*	Hokkaido Natl. Agri. exp. Stn	1981
Toyonishiki	*Pia*	*Pii, Pik, Pita, Pita-2, Piz-t*	Tohoku Natl. Agric. Exp. Stn.	1988
Koshinishiki	*Pik-s*	*Pia, Pii, Pik, Pik-p, Pik-m, Piz, Piz-t, Pita, Pita-2, Pib*	Niigata, Toyama, and Fukui Prefecture	
Hinohikari	*Pia, Pii*	*Pik-m, Pita, Pita-2*	Miyazuki Precture	
Maihime	*Pia*	*Pii, Pik-h, Pik-m, Piz, Pita, Pita-2 Piz-t, Pib*	Aomori Prefecture	
Hanaechizen	*Piz*	*Pik, Piz-t, Pita, Pita-2, Pib*	Fukui Prefecture	
Etsunan 157	*Pia*	*Pii, Piz, Piz-t, Pita-2*	Fukui Prefecture	
Mineasahi	*Pia, Pii*	*Pik, Pik-m, Piz, Piz-t, Pib,Pita, Pita-2*	Aichi Prefecture	
Chubu 64	*Pii*	*Pik, Pik-m, Piz, Piz-t, Pib,Pita, Pita-2*	Aichi Prefecture	
Kinuhikari	*Pii*	*Piz-t, Pib, Piz, Pita-2*	Hokuriku Natl. Agric. Exp. Stn.	
Akitakomachi	*Pia, Pii*	*Pik, Pik-m, Piz, Piz-t, Pita, Pita-2, Pib, Pit*	Akita Prefecture	

Near-isogenic lines that are being developed.

GD Table 3. Grain yield and blast infection of mixtures of different rice varieties and hybrid populations (F_3-F_4) of eight japonica varieties compared with pure stands. Recomputed by Chang and Oka (1987) from Chang and Chao (1977).

Measurement	Mixture	Hybrid populations
Grain yield, increment	n=38	n=36
(X/MP - 1) x 100	1.9 +/- 0.93%	6.5 +/- 1.05%
Blast infection score[a]	n=8-0.56	-1.58
difference (1972)		

MP: Mid-parent value for each mixture or hybrid.

All four values in the table differ from zero significantly.

[a.] Leaf infection index, 10 classes from 1 to 120 with logarithmic class intervals, converted into scores of 0 to 9.

GD Table 4. Yield and estimates of yield stability of pure, mixed, and hybrid populations of three indica varieties.[a]

Population	Grain yield (kg/ha)	Regression coefficient [b]	α for deviation from regression
Pure	5,934	0.98	1.406
Mixed	6,032	1.02	0.925
Hybrid	6,393	0.99	1.121

[a] Three varieties, three mixtures, and three hybrids tested over 5 seasons; after Chang and Chao (1977).
[b] On environmental means (cf. Finlay and Wilknson 1963--not in reference list).

GD Table 5. Yield performance and leaf blast infection grade of multiline cultivars of rice, compared with those of mother varieties. Source: Chiu and Teng (1975).

	Relative grain yield		Leaf blast[a]		Panicle blast[b]	
Variety	Winter	Summer	Winter	Summer	Winter	Summer
Tainan 5	100	100	36	85	38	39
Multilines[c]	108	164	2	4	18	13
Chianung 8	100	100	50	89	41	47
Multilines[d]	130	168	5	5	14	8

[a.] Leaf blast infection index, 10 classes from 0 to 120 with logarithmic class intervals.
[b] Infected panicles in percent of total panicles.
[c] Mean for four different composites each composed of three semiisogenic lines with different resistance genes, with the genetic background of Tainan 5.
[d] Same with genetic background of Chianung 8.

The extent of change per generation and its subsequent economic effect need future investigation. Seed renewal every 3 years is common, even when homogeneous varieties among farmers are used. However, there is still no guarantee that the ratio of R- and S-variety remains the same.

It may be necessary to develop a procedure for predicting the performance of varieties in mixtures. Instead of merely selecting varieties at random, genetic markers may be used to select varieties based on performance and compatibility. Researchers are exploring the use of genetic distance between varieties as a parameter to predict the performance of mixtures in the field, specifically in terms of yield and disease resistance. Genetic distance between varieties in Yunnan, China, was determined using molecular markers where the correlation between genetic distance and performance in farmers' fields could be quantified and determined (Zhu et al 2001).

4. Need for genetic diversity

In agricultural development, crop breeding, especially in a self-pollinated crop such as rice, usually begins with pure-line selection. Fixing the selected lines after hybridization into a genetically homozygous state is an important requirement of the process. Varieties developed through this process are released to farmers or for commercial production. This process results in a monoculture system in modern agriculture. Using the "Green Revolution" era as an example, soon after variety IR8 was first released and planted by farmers, it was realized that resistance to a few major diseases was prerequisite for a variety to be successful in tropical Asia. Deployment of varieties with resistance to the major diseases became an important objective of varietal improvement.

In disease management, variety with disease resistance is effective and attractive as it requires no additional cost to resource-poor farmers and is environmentally safe. The dilemma in following this approach is that a single resistance gene against a plant disease with polycyclic epidemic potential is often used repeatedly and deployed over wide geographical areas. Due to selection pressure, the resistance gene becomes ineffective when a new virulent strain of the pathogen emerges. This is best exemplified by rice blast caused by *M. oryzae*. Consequently, new resistance genes are sought and bred into new crop varieties to which new strains of the pathogen will then adapt, failing its productivity. This creates the "boom-and-burst" cycle that has become a phenomenon, which critics of modern agricultural development have accused researchers of creating a monoculture system that unintentionally destabilizes rice production. More importantly, and not often mentioned, this approach is also exhausting limited genetic resources.

On the other hand, the populations of traditional varieties or landraces that remain unimproved are genetically heterogeneous and are said to be less prone to pests and diseases. The genetic diversity in these traditional varieties seems to indicate their stable performance (Harlan 1975). Because of the range of resistance genes they may possess, they have a buffering effect to the coevolution of the pathogen with the resistance genes. Although their yield is low, their production seems to be more stable (Osiru 1983). However, the low productivity of this system is feasible only for subsistence farmers in unfavorable production environments when the human population is still low and rice crop production is meant just for feeding household members, but cannot meet the food demand of an increasing human population as seen over the past decades.

In the 1980s and 90s, the rate of rice production gradually declined by less than 1% but the human population continued to increase at a rate well over 1%, which concerned the policymakers (Hossain et al 2003). The reduction in arable land and other natural resources, such as water needed for rice production, has faded the optimism created by the

Green Revolution. To secure crop improvement, enhancement of genetic diversity of the newly developed rice varieties is a very effective option. Although genetic diversity in rice cultivation and resistance breeding is both feasible and desirable, it will be challenging to attain in modern rice improvement, development, and production. Emphasis on resistance gene management or R-gene deployment has never been so close to the heart of the problem of modern rice production. Genetic diversity through R-gene management is truly a sustainable approach. It will involve effectively deploying R-genes by prolonging their usefulness, consequently optimizing the use of the limited genetic resources available.

The advantage of genetic diversity may be viewed from two different perspectives. Information has shown variations on genetic diversity provided by variety mixtures and multiline varieties. Variety mixtures provide two levels of heterogeneity: the specific disease R-genes that may reduce the epidemic of a disease and, equally important, the genetic background of the component varieties, which is associated with the mixture's other agronomic characters, such as yield gain and grain quality (Wolfe 1985). In a multiline variety, the background resistance of the recurrent parent, either complete or partial, may be important in providing additional resistance to a target disease (Koizumi 2001). For practical considerations, in fragile rice production environments such as upland or unfavorable rainfed areas in tropical Asia, genetic diversity can contribute to household food security by providing stable production—even if low-yielding varieties are used. Interplanting high-quality traditional varieties with a modern high-yielding variety allows farmers to retain the continuous production of their local traditional varieties with a high market value for additional income (Revilla et al 2001). In a traditional rice production system, a single field is often planted with more than one rice variety. The system may be improved by choosing the right traditional varieties that can be grown together with a modern one on a purposeful interplanting design. Introducing variety mixtures to a cropping system cannot only help prevent pest outbreaks and disease epidemics in intensive rice production system but can also result in stable crop production with low inputs for subsistence farmers. Studies on stripe rust of wheat (Mundt 1994), powdery mildew of barley (Wolfe 1992), and blast of rice (Zhu et al 2000) demonstrate that genetic diversity is an effective means to prevent epidemic diseases and result in stable crop production.

4.1. Advantages of genetic diversity

If a choice is needed, variety mixtures may be more advantageous than multiline varieties because, in the former, a target pathogen must respond to both adaptation and adaptability of the background resistance of the component varieties (Wolfe 1985) while the latter differs only in the R-gene possessed by the component lines. More importantly, the variation in genetic background of the cultivar mixture can help control nontarget pathogens. In contrast, a number of multiline varieties have been proven to be uniformly susceptible to nontarget pathogens (Wolfe 1985).

Susceptible plants are less infected in a mixed stand than in a pure stand because of the loss of dispersing pathogens on resistant plants. In addition, the loss of grain yield in susceptible plants can be mitigated by the compensative growth of resistant plants. Such effects may be the source of field resistance of composite and multiline varieties to diseases and insect pests.

Effective rice cultivar mixtures can be put into practice if farmers accept them. They reduce target diseases, such as blast, and reduce the use of agricultural chemicals such as pesticides. The Yunnan experiment also suggested that fungicides for control of blast disease would not be necessary when interplanting a resistant variety (main component) and a susceptible variety (secondary component for high specific quality and market value) (**GD Table 6**).

4.2. Is there a yield gain or penalty?

The use of cultivar mixtures is an inexpensive and simple strategy for disease management that can be added to or integrated with other strategies. It improves efficiency and reduces the use of fungicides, which is desirable both economically and environmentally. More importantly, all multiline varieties and cultivar mixtures tested so far have showed higher yield and better grain quality than the variety used as the recurrent parent or the component varieties individually in a cultivar mixture (Wolfe 1985, Finckh 1998). It is uncommon for a mixture to yield less than the mean of its components and rare for it to be as low or lower than the worst component (Wolfe 1985, Smithson and Lenné 1996, Mundt 2002). The drawback in using multiline varieties is that it takes longer to breed and a lot more technical labor to develop than conventional varieties. When a multiline variety has been bred and commercialized, it is already behind the times. Moreover, if a multiline variety aims at a specific disease, it has not been proven effective against any other diseases (Wolfe 1985).

The key to the yield advantage in a mixture is in the "mix." In a seed mixture, different results were obtained when different proportions of the rice varieties were mixed. The difference between pure and mixed varieties depends on the component varieties not only for yield but also for disease suppression (Chiu and Teng 1975). If the higher proportion in a seed mixture is low in disease resistance or yield, then the disease reduction or yield gain may not be very significant. This was further confirmed in an experiment for blast control in upland rice in Indonesia (N. Castilla, International Rice Research Institute, unpublished results). When four or six rows of a high-yielding semidwarf variety susceptible to blast was interplanted with one row of a resistant traditional tall variety, blast was not suppressed. If the R-component is less and S is high, the reduction of blast is not likely to be achieved. More importantly, the Indonesian case also suggested that the barrier effect of the plant height provided by the tall resistant component was largely diluted by the dense but shorter susceptible component. Thus, the effect of a varietal mixture to suppress blast was lost, a result that is dramatically different from the Yunnan case of varietal interplanting 1 row of a tall, susceptible traditional glutinous rice with 4 to 6 rows of a modern resistant variety for blast control.

The eating quality of grain coming from a mixture can be improved by proper blending of selected varieties. On a commercial scale, this can be practiced with advanced knowledge of the grain quality of the components (Okabe 1979). Proper blending of rice varieties can ensure premium rice in the market.

GD Table 6. Influence of inter-planting of hybrid (blast resistant) and glutinous (blast susceptible) rice on cost savings from pesticides use. Source: Leung et al (2003).

Items	Adopters	Nonadopters
Numbers of sprays	1	3
Cost of pesticides (USD)	1.50	4.42
Labor for pesticide application (day)	0.63	0.76
Imputed cost of labor (USD)	1.98	2.86
Total cost (USD/ha)	3.48	7.28
Financial benefit (USD)	3.80	

The case was demonstrated by the Yunnan study that involved interplanting of high-quality glutinous rice with high-yielding hybrid rice. Because of the differential maturity of the component varieties and the harvest (manual) was done according to the maturity of the individual varieties, grain quality is intact with each variety (Zhu et al 2000, Revilla et al 2001). The results showed total yield that was never less than pure stands of either component variety. Other desirable effects of interplanting "one row of a tall traditional variety with four to six rows of semidwarf hybrid rice" include the physical support provided by the short-statured hybrid rice to the tall traditional variety, thus preventing lodging of the tall variety (**GD Figure 3**). Lodging alone may cause a yield penalty of one ton of rice when it occurs at flowering stage of the rice crop (T.W. Mew and N. Castilla, International Rice Research Institute, unpubl.). Thus, the disadvantages of the Yunnan model of genetic diversity, i.e., interplanting a tall traditional high-quality rice with an improved high-yielding semidwarf variety, include: (1) the proportion of the tall to short cannot be increased to the point of causing lodging and (2) increasing the plant population of the blast-susceptible, tall traditional variety also increases blast incidence. Koizumi and Kato (1987) reminded of a similar concern in the R:S ratio in a blend of isogenic lines in a multiline variety against blast.

GD Fig. 3. Significant yield loss due to lodging of a tall variety.

5. Restricting disease spread

Genetic diversity achieved through multiline varieties or varietal mixtures has been effective against airborne pathogens with host specificity. This has been demonstrated on rust diseases of wheat and oat, powdery mildew of barley, and blast of rice. The successful examples come from large-scale commercial plantings as shown in the case of powdery mildew of barley using a seed mixture and in rice blast using interplanting.

The functions of genetic diversity include reducing the spread of the disease epidemic and slowing the evolutionary process of the pathogen in adapting to the new resistance (Leonard 1969, White 1982). Disease suppression in relation to varietal mixture has something to do with, first, the disease in spatial density of susceptible plants, second, the barrier effect provided by resistant plants that fill the space between susceptible plants, and, third, the resistance induced by nonvirulent spores that landed on incompatible plants (Wolfe 1985, Garrett and Mundt 1999). Other mechanisms may exist as suggested by the interplanting of a tall glutinous variety and semidwarf hybrid rice (Zhu et al 2005). The reduction in humidity, dew point, and duration between the two components of different heights was not favorable to blast development. The unfavorable microclimatic conditions created by the interplanting could be the reason for reduced blast on the susceptible glutinous component in the interplanting.

The decrease in spatial density of susceptible plants affects disease incidence by reducing the infection efficiency of new inoculum from the lesions (Wolfe 1985). Potentially, it also reduces the survival of the spores leaving the parent lesion, as fewer spores are likely to reach a neighboring susceptible plant. Clearly, the lower the density of the susceptible plants, the lower will be the rate of the new infection from the newly released spores. This signifies the importance of pattern efficiency of the ratio between the resistant and the susceptible varieties in the mixture. The barrier effect enhances the first mechanism provided by the resistant plants that fill the space between the susceptible plants. The architecture of the "crop canopy" created by both the resistant and the susceptible plants may play a role in regulating the effect of the epidemic process, especially in relation to microclimates. Induced resistance results from failure to infect by spores that land on the same area on the resistant plants. The Yunnan study has shown that the climatic conditions for the disease development could be regulated by interplanting of tall- and short-stature varieties. In such a case, the ratio of the resistant and susceptible varieties in interplanting is crucial in taking advantage of its effect on disease development.

A varietal mixture may influence the infection efficiency of an inoculum. If the inoculum is from an outside source, the mixture simply provides a spatial effect. However, if the inoculum is generated within the canopy of the varietal mixture, the survival of the inoculum is affected. Against a foreign inoculum, the amount of infection caused by an exogenous spore shower landing on a mixture equals to the mean infection of the components. It is upon the product of the initial infection that the mixture has its unique effect in limiting the spread of the pathogen population (Wolfe 1985).

In a vector-transmitted virus such as rice tungro, the efficiency of the mixture appears to bear a strong relationship to the feeding behavior of the vector. In rice tungro, the vector of the virus, green leafhopper, *Nephotettix virescens*, moves less while feeding on a susceptible than on a resistant plant (Ling 1969, 1976). In resistant varieties, the green leafhopper t ends to punch and move instantaneously from plant to plant in searching for the "right" plants to feed.

Green leafhoppers tend to stay on susceptible rice plants for feeding until the infested site is exhausted in nutrients, then they move to another location on the same plant or to a different plant. Hence, to prevent vector feeding, it is more effective to use a seed mixture than to interplant resistant and susceptible varieties (**GD Table 7**). In managing rice tungro in the Philippines, farmers prefer a seed mixture with a 1:1 ratio of a susceptible variety and a resistant variety than interplanting by following the Yunnan pattern (I.R. Choi, pers. comm.). Experiments conducted in farmers' fields showed that the effectiveness of a seed mixture depended on the proportion of resistant and susceptible varieties and on initial disease incidence.

GD Table 7. Rice yields from pure stands and mixtures of Matatag 9 and IR64 during crop seasons WS 2003-4 and 2003-4 in Iloilo and Cotabato Provinces, respectively, Philippines.

	Yield (t/ha)				
Province/Crop Season	4:00	3:01	1:01	1:03	0:04
Iloilo					
Late WS 03	3.3 (100)	3.7 (111)	3.7 (113)	3.9 (118)	4.2 (128)
Late DS 04	4.1 (100)	4.1 (100)	4.4 (107	4.6 (111)	5.1 (220)
Cotabato					
Late WS 03	4.9 (100)	3.5 (126)	4.3 (158)	4.4 (161)	4.7 (172)
Late DS 04	1.4 (100)	1.5 (106)	1.8 (130)	2.7 (192)	3.1 (220)

When levels and functions of the component genotypes are favorable for pathogen infection, the advantage of mixtures appears to be diminished. Under upland rice conditions, when the tall traditional variety is resistant, a pattern of interplanting one or two rows of this variety with four or six rows of a high-yielding but blast-susceptible semidwarf variety, the advantage of interplanting disappears as demonstrated in Yunnan (Zhu et al 2000). Indeed, it is back to the issue of the R:S ratio and perhaps also on microclimatic conditions created by the mixture in favor of blast development. In a "right mix", the mixtures appear to exert their effect of limiting disease after they have begun to produce their own inoculum. The seed mixture, which is a random distribution of R and S plants, is less effective against repeated introduction of exogenous inoculum. The probability of landing on the susceptible plants is 50%. Thus, the more incoming inoculum (repeated introduction), the higher is the probability of infection. This may also explain why the effectiveness of disease control in mixtures declines with the increasing length of growing season.

One of the major concerns surrounding the use of multiline and varietal mixtures is the establishment of complex races. Available information seems to suggest that the lack of fitness of super races in a natural population may affect their survival and lower their rate of reproduction (Barrett and Wolfe 1978). As suggested by Wolfe (1985), the best management option when using a mixture is to diversify the components. The reality in agriculture is that one should not expect that any host plant, either as a pure line or in a mixture against a plant disease, will last indefinitely. It depends on which offers a longer lasting effect on the useful life of the host varieties and on inducing evolution of the pathogen virulence. The overall strategy, therefore, requires the change of components in space and time to exert disruptive selection on the pathogen population. Such a system will prevail because it allows new varieties to be continuously integrated into different mixtures containing high-quality traditional and modern varieties.

5.1. Genetic diversity against nonspecialized pathogens

So far, all successful examples of mixtures of host genotypes in suppressing plant diseases are based on diseases caused by specialized pathogens. There is no clear evidence that a mixture of host genotypes is equally effective in restricting the development of a nonspecialized pathogen. There has been little research on varietal mixtures to reduce diseases caused by nonspecialized pathogens. Some reports appear to show a positive reduction in disease while others show inconsistent results. In wheat infected with *Septoria nodorum*, a nonspecialized and splash-dispersed pathogen (Jeger et al 1981), a reduction in disease incidence was observed. Using four mixtures of moderately resistant and susceptible winter wheat varieties naturally infected by *Mycosphaerella graminicola* (*Septoria nodorum*), Cowger and Mundt (2002) investigated their impact on disease progression in the field and the effects on pathogenicity of the pathogen populations sampled from the field on greenhouse-grown seedlings. Over a 3-year period, they concluded that the ability of mixtures challenged with *M. graminicola* to suppress septoria blotch appeared to be inconsistent. In such a system, mixtures of a host genotype with moderate resistance did not consistently confer resistance to suppress the disease. Varietal mixtures are also less effective in suppressing disease when initial inoculum is abundant and well distributed (Mundt and Leonard 1986). Against *Rhynchosporium secalis*, a splash-dispersed pathogen, a mixture of barley varieties was not effective in managing the numerous disease foci in the field (Abbott et al 2000). Garrett and Mundt (1999) hypothesized that this could be due to the fact that, although the wheat blotch is a foliar disease, it is caused by a rain-splash dispersed pathogen in which the mixture seems to be less effective. Mixtures are expected to be effective when there is an exchange of inoculum among plants. In the case of interplanting, it may not be effective in managing rice diseases, such as bacterial blight, whose inoculum is produced on the plant or its immediate neighbors. Under such cases, the resistant varieties could not be effectively restricting the spread of inoculum from one plant to another.

In the experiments of rice interplanting for blast control conducted in 1997-99, in Yunnan, China, we observed high incidence of sheath blight and false smut on both component varieties (T.W. Mew, International Rice Research Institute, unpubl.). This could be due to the fact that both rice varieties were susceptible to both diseases. Thus, the effect of the host mixture, either seed mixture or interplanting, seems to have less effect on nonspecialized pathogens. Even against some foliar pathogens, the pattern of epidemic development affects the effectiveness of genetic diversity through the varietal mixture.

6. A case study on genetic diversity: the Yunnan experience

The most publicized experiments on genetic diversity in recent years may be those on rice variety interplanting for blast control conducted in 1997-99 in Yunnan, China (Zhu et al 2000), which the *New York Times* reported that it was possibly the largest experiment ever conducted on genetic diversity (Yoon 2000). The pattern of genetic diversity was by interplanting one row of a tall, high-quality traditional glutinous variety with four to six rows of a high-yielding semidwarf hybrid. The glutinous rice was susceptible to blast while the hybrid was resistant. The blast on glutinous rice was reduced by more than 90% as compared with pure stand.

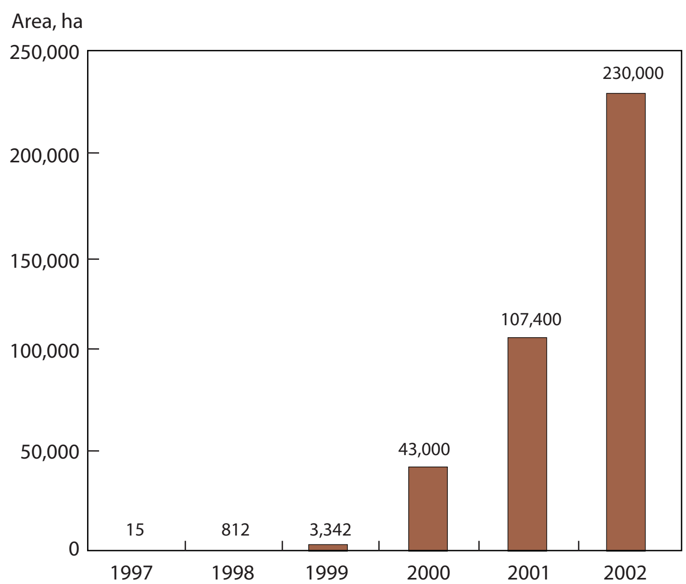
Obviously the blast epidemic on the susceptible glutinous rice was controlled. The experiments demonstrated that inter-planting the susceptible glutinous rice with the resistant hybrid rice consistently reduced rice blast incidence and severity, and increased the yield gain of the susceptible variety by 90%, while maintaining the yield of the resistant variety (**GD Table 8**) (Leung et al 2003). When the first set of experiments was conducted in farmers' fields with their participation, the farmers understood what was done and appreciated the experiment's outcome. It seems that the simplicity and effectiveness of the approach had attracted more farmer participation from nearby villages in the next series of scale-up testing. The local agricultural technicians coordinated training of other farmers in other villages, which was supported by local and provincial governments. The technical support to this set of activities was provided by scientists from the collaborating institutions, Yunnan Agricultural University and IRRI.

GD Table 8. Mean yields of glutinous and hybrid rice by type of farmer[a], Yunnan Province, China, CY2000. Source: Leung et al (2003).

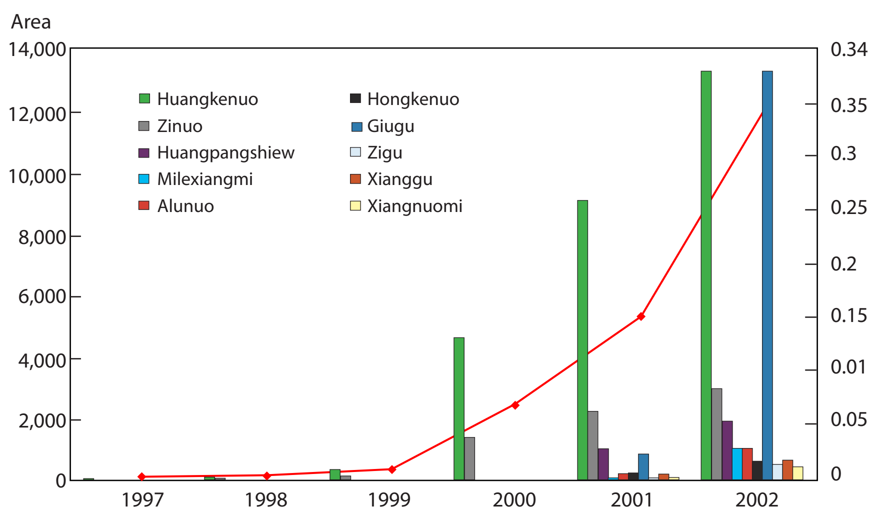
		Adopters		Nonadopters	
Rice yield (t/ha[1])	1998-99	2000	Differences	2000	Difference
Glutinous rice	2.13	2.14	0.01[b]	0.42	1.72[c]
Hybrid rice	8.87	8.94	0.07 ns	9.15	-0.21 ns
Total	11	11.08	0.08[d]	9.57	1.51[e]

[a] Farmers who did or did not adopt a diversification scheme.
[b] $t = 0.032$, $P<0.10$.
[c] $t = 5.083$, $P<0.001$.
[d] $t = -1.483$, $P<0.05$.
[e] $t = 3.365$, $P<0.10$.

By the end of 2001, about 60% of the rice farm households in the indica rice-growing region of Yunnan Province had adopted interplanting of rice varieties and the area had been expanded to more than 100,000 hectares (**GD Figure 4**). Within a 5-year period, the traditional high eating-quality varieties had occupied a very substantial indica rice production area in the province and the diversity index increased to 35% (**GD Figure 5**). The approach also suggested a potential opportunity to promote on-farm conservation of traditional rice varieties in other countries by experimenting with the interplanting method using both traditional and high-yielding modern rice varieties (Zhu et al 2003).



GD Fig. 4. Area under rice interplanting, 1997-2002, Yunnan, China.



GD Fig. 5. Proportion of area planted to different traditional varieties and index of genetic diversity, Yunnan Province, China, 1997-2002.

Although the use of relatively few highly productive plant varieties has dramatically increased food production in many regions of the world, concerns have arisen that traditional landraces with high adaptability to heterogeneous environments are irreversibly displaced and lost as a trade-off. An important question to ask is whether sustained productivity can go hand-in-hand with the preservation of genetic diversity. It is of little doubt that on-farm preservation of traditional landraces is difficult to sustain unless it contributes to better livelihood for farmers. It is, therefore, important to develop a production system with built-in incentives for conserving high-value traditional landraces. For most farmers, this would mean a production system that would improve income as well as livelihood in the rural areas. The experiments in Yunnan, indeed, have demonstrated that this can be done. The traditional glutinous rice, although low in yield has high market value that compensates the difference (Revilla et al 2001).

Scale is an important consideration in testing the effectiveness of genetic diversity (Mundt 2002). The experiment on genetic diversity has to be relatively large in plot size or scale before its full potential is shown as confirmed by the Yunnan experiment. The other important factor based on the Yunnan experiment is how to scale-up a potential production strategy for crop production and disease management. The success on scaling-up the Yunnan experiment concomitantly with its field experiments was attributed to several factors as observed by world renowned social scientist, Prof. G.T. Castillo. In her synthesis (Castillo 2002) of an impact symposium about the project in which the experiments in Yunnan was tabled around a major part of the field visits and discussion, she made the following observations.

- The scientists played an active role in the research translation process. This translation of technical research results into farmers' participatory learning cannot be just passed on to somebody else. It involves farmers, extension workers, and policymakers.
- Farmers' participation came early in this project and in a very significant way in demonstrations of the effect on interplanting of a traditional variety with a modern one in their fields.
- The on-farm training effort was intensive and massive.
- This was a case in which modern science meets local knowledge.
- It is, however, a team effort involving interdisciplinary research with a clear set of objectives.

6. Conclusions

The Yunnan case study demonstrates that genetic diversity is important in designing a sustainable crop production system with disease pest management in mind. Whether it is achieved through developing a multiline variety or interplanting of compatible genotypes, it is important to have a full understanding of the problems and outline the target and path of achievement. There is no one single method that works for all environments. In project implementation, the approach has to be tailored to farmers' practices of crop production and characteristics unique to the pathosystems. Seed management is an important issue in implementing genetic diversity. A community approach, especially targeted at less developed countries, should be considered. It is also a way to organize farmers. Technically, genetic diversity is not effective for all diseases. Even for blast, to achieve genetic diversity either through multiline or interplanting, the "right mix" depends on the genetic composition of the varieties. For other rice diseases, genetic compositions of the component varieties and knowledge of the epidemiological process determine the diversification strategies that are most appropriate for certain production environments.

The important lesson learned from the Yunnan experiments is the diversification concept. Diversification can be effective and agronomically feasible only if the implementation strategies are compatible with farmers' cultural practices and if the results are economically attractive. To scale up a technology, it is important to involve all key partners from the very beginning of the research.

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