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Using Genetic Diversity to Achieve Sustainable Rice Disease Management

Host plant resistance is an important tool for rice disease control and has played a key role in sustaining rice productivity, especially in tropical Asia. Deploying resistant varieties as a means of disease control is attractive because it requires no additional cost to farmers and is environmentally safe (62). Furthermore, resistant varieties can be easily disseminated as seeds, leading to wide adoption (12). These are important considerations, because for resource-poor rice farmers in developing countries, the options for managing diseases are few. For example, during the 1970s and 1980s, when epidemics of rice tungro were frequent in the Philippines and Indonesia, farmers expressed more confidence in using resistant varieties than in other control measures. Disease control using chemicals is more common in the temperate or subtropical production environments where farmers apply fungicides for controlling blast (caused by *Pyricularia grisea*) and sheath blight (caused by *Rhizoctonia solani*). Despite regional differences in control measures, planting resistant varieties is considered most effective by rice farmers. Hence, breeding for disease resistance has been a major objective in rice improvement programs conducted at international agricultural research centers, such as the International Rice Research Institute (IRRI), and at the national agricultural research systems (NARS) of developing countries.

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There are limitations, however, in using resistant varieties alone to manage rice diseases. Most varieties are resistant only to a few major diseases that are the subjects of intensive breeding efforts. The rice production environments, particularly in the tropics, are habitats of many rice pathogens causing varying degrees of damage. Even the "minor" diseases collectively could pose a significant threat to production (63). Thus, pathologists and breeders have to deal with yield loss caused by diseases of epidemic and endemic nature. Epidemic loss is dramatic but less frequent, whereas endemic loss is less obvious but pervasive in each cropping season. Recent surveys indicated that an estimated annual yield loss from 1 to 10% was due to a combination of different diseases (80). Thus, resistance against a few targeted diseases offers only a partial solution to rice disease problems. To those diseases caused by nonspecialized pathogens, such as sheath blight and false smut (caused by *Ustilaginoidea virens*), no useful source of resistance has been identified to improve the resistance of rice varieties. To achieve sustainability of rice production in Asia, we need a rice production system built upon effective resistant varieties with broad resilience to a range of diseases and insect pests. Broad-spectrum resistance at the genotypic level and sustainability at the cropping systems level are therefore complementary approaches in managing rice diseases. Although considerable progress has been made over the past decades, much more can be done to integrate these two approaches to achieve results in farmers' fields.

Modern agricultural development has transformed the diverse, traditional rice production system into a monoculture system that relies only on a few fertilizer-responsive and high-yielding varieties. Farm-

ers' preference to high yield has led to wide adoption of modern rice varieties cultivated in millions of hectares of rice land. Although most modern varieties have built-in resistance against multiple diseases, genetic uniformity inevitably predisposes the system to disease epidemics, and under certain circumstances can lead to serious yield loss caused by diseases and insect pests (43). Varieties carrying a few resistance genes in a uniform genetic background are vulnerable to rapid adaptation of pathogens and pose uncertainty to farmers. For instance, emergence of new pathogen races caused several blast epidemics in Korea in the 1970s, leading to yield losses of 30 to 40% (38). In the 1980s, other disease outbreaks on a regional scale included epidemics of bacterial blight in northern India and Southeast Asia, tungro in Southeast Asia, and bacterial blight and blast in Japan (38,61,89).

Another impact of the monoculture system is the gradual decline in the diversity of varieties grown by farmers. As modern high-yielding varieties expand to millions of hectares, they also replace the traditional varieties. Although useful genes from these traditional varieties are being used in breeding for modern varieties, many unique attributes and gene combinations resulting from years of selection are difficult to reconstitute. To achieve the productivity needed, it is not possible to revert to planting diverse traditional varieties that are poor yielding. However, it is within our capacity to work toward disease management methods that sustain productivity yet maintain adequate diversity and resilience in the production systems.

In the past two decades, IRRI has moved toward increasing genetic diversity of modern rice varieties through resistance breeding (12,39,43) and deployment of different resistance genes based on an un-

derstanding of the pathogen population structures (52,54,55). This research strategy embraces the principle that genetic diversity is an effective mechanism for reducing disease damage in natural ecosystems, and that it can be used to manage plant diseases to avert crop loss in modern agriculture (15,95). These research activities culminated in the initiation of a project entitled “Exploiting biodiversity for sustainable pest management” in 1996 with support from the Asian Development Bank (76). One of the highlights of this research initiative is the collaboration with Yunnan Agricultural University in applying mixed planting of traditional glutinous rice with modern hybrid rice as a means for blast control. The research suggests a way to manage diseases through the deployment of genetic diversity on a large scale. As a result, farmers’ income increases through

yield gains and reduced pesticide use. More importantly, it also suggests a way to conserve traditional varieties sustained by economic incentives.

The Yunnan study has stimulated considerable interest in extending the principles of genetic diversity for disease control in other crops in developing countries. It is therefore timely to discuss the research “road map” leading to the use of functional diversity to control rice blast and how the experience gained in Yunnan can be used to improve disease management in the future. We will first review the status of rice disease management and the knowledge and tools available to support various options. We then highlight the experiments conducted in Yunnan and present additional case studies that extend the diversification concept to other diseases and cropping systems. We will conclude by discussing the future prospects of applying

biodiversity to sustain productivity and germplasm conservation.

Disease Resistance: Key to Sustaining Productivity

Yield gains due to genetic improvement. Since the first release of the “miracle” rice variety IR8 in mid-1960, we have witnessed continuous gains in rice productivity up to the present day. This remarkable increase in rice yield has served to achieve food security in Asia (28). At least three factors have made this successful technological change possible: (i) continuous effort in the development of high-yielding semidwarf rice varieties by public research institutions and making the seed freely available to farmers, (ii) the dramatic yield increase provided by the improved varieties, leading to rapid adoption by farmers, and (iii) parallel improvement in farming infrastructure to support the

Table 1. Major diseases of rice showing symptoms, the causal organism, prevalence, and management strategies

Rice disease	Symptom ^a	Causal organism	Prevalence (affected region and ecosystem)	Management strategy	
				Resistance (R) gene-based	Resource-based
Rice blast		<i>Pyricularia grisea</i> (anamorph) <i>Magnaporthe grisea</i> (teleomorph)	Tropical and temperate regions worldwide in upland and lowland ecosystems	Durable resistance (13) R gene pyramids (33) R gene rotation (22) ^b Cultivar mixture (102) Multilines (49) Transgenic resistance (68) ^b	Biological control agents (65) ^b Silicon application (24) ^b Nitrogen and water management (83) Field sanitation (83) Fungicides (62)
Bacterial blight		<i>Xanthomonas oryzae</i> pv. <i>oryzae</i>	Tropical and temperate regions worldwide in lowland ecosystems	Durable resistance (66) R gene pyramids (34) Cultivar mixture (2) ^b Transgenic resistance (68) ^b	Nitrogen management (75) Field sanitation (64)
Rice tungro		Rice tungro bacilliform and spherical virus	Tropical regions in Asia in lowland ecosystems	Host plant resistance (6) Rotation of GLH-resistant varieties (58) Transgenic resistance (6) ^b Cultivar mixture (74) ^b	Synchronous planting (79) Field sanitation (6)
Sheath blight		<i>Rhizoctonia solani</i> (anamorph) <i>Thanatephorus cucumeris</i> (teleomorph)	Tropical and temperate regions worldwide in all ecosystems	Transgenic resistance (26) ^b	Biological control agents ^c Silicon application (77) ^b Fungicides (62) Crop rotation (62) Field sanitation (62) Nitrogen management (23)
Brown spot		<i>Bipolaris oryzae</i> (anamorph) <i>Cochliobolus miyabeanus</i> (teleomorph)	Tropical and temperate regions worldwide in upland and rain fed ecosystems	Host plant resistance (73) ^b Cultivar mixture (32) ^b	Silicon application (25) ^b Fungicides (73) Field sanitation (73) Proper soil nutrition (73)

^a Photographs courtesy of N. Castilla and S. Savary, IRRI.

^b Mostly at experimental stage, not yet widely practiced.

^c T. W. Mew, B. Cotyn, R. Pamplona, H. Barrios, X. Li, Z. Chen, F. Lu, P. Arunyanart, N. Nilpanit, D. Rasamee, P. V. Kim, and P. V. Du. Applying rice seed-associated antagonistic bacteria to manage rice sheath blight in developing countries (*unpublished*).

cultivation of these modern varieties. Average rice yields in all developing countries rose by 914 kg ha⁻¹ from 1961 to 1980 and by 1,128 kg ha⁻¹ from 1980 to 2000 (28). Nearly 50% of these yield gains were produced by crop genetic improvement (27,28).

Disease resistance to secure the yield gains. Different genetic components are responsible for the crop productivity gain of more than 2% per year since the 1970s. Among these, host plant resistance against diseases no doubt plays an important role. Table 1 shows the main rice diseases causing varying degrees of economic damage in tropical Asia and the management practices currently used or being explored. The damage caused by these diseases is a function of the prevalence of the pathogen, epidemic potential of the disease, and available control measures. Fortunately, for the most serious diseases with high epidemic potential, control by host plant resistance through genetic means is possible.

Disease resistance contributes to rice yield increase in two ways. It reduces yield loss due to diseases, and it expands the adaptability of rice varieties to production areas previously limited by high incidence of diseases (27). For instance, economic impact analysis from India suggests that modern varieties with built-in disease resistance likely contribute 7 to 10% yield gain in rice production (27). However, there are other diseases in tropical rice production ecosystems that collectively cause chronic yield losses and destabilize annual production. Furthermore, as cultural practices and cropping intensity change over time, some previously "minor" diseases become serious problems. Nearly all resistance breeding efforts are directed against the major diseases with high epidemic potential. It is not known whether the overall improvement in resistance has any effect on endemic diseases. As rice production systems evolve, the relative economic damage caused by different diseases needs to be updated in order to sustain the yield gain.

Changing production scenarios. To assess the current rice disease problems, Savary et al. (80,81) combined field survey data and controlled experiments to determine the production constraints and yield loss under different production scenarios. The group applied nonparametric statistics to quantitatively define rice cropping patterns of various production situations, pest profiles, and crop loss. The results showed that among the many diseases occurring in rice fields, sheath blight and brown spot account for the highest yield loss (6% for sheath blight and 5% for brown spot) across all production situations in South and Southeast Asia. Rice blast, with a high potential to cause severe epidemics across Asia, is estimated to cause a 0.3 to 5% yield loss, while bacterial blight causes losses of less than 1%.

The results of Savary et al. (80,81) seem to contradict conventional thinking on the relative importance of different rice diseases. For example, brown spot has always been considered a disease resulting from poor soil fertility and was not included as a target for disease resistance breeding. However, when viewed in a historical context, the study provides important insights on the changing production scenarios and the shifting problems over time. First, the surveys indicated that the most serious diseases prior to the late 1970s posed a lesser threat to rice production in the late 1990s, even though they can still cause severe epidemics when resistance is insufficient. They support the notion that the sustained efforts of resistance breeding started in the 1960s to 1970s against blast and bacterial blight, and later against tungro, have paid off. Second, diseases such as sheath blight and brown spot become prominent due to either a lack of effective resistance in the germplasm or a lack of breeding effort. The challenge ahead is to develop broad-spectrum resistance and production systems that suppress a multitude of biotic stresses. To meet such a challenge, research on host plant resistance must evolve not only to respond to the emerging problems but also to capture advances in new science to enable better use of genetic resources in managing diseases.

Finding the Right Genes

In collaboration with many rice research and breeding institutions, IIRI has taken two approaches to manage rice diseases: incorporating different resistance genes into new varieties, and designing deployment strategies using varieties with different resistance genes. Both approaches rely on the identification of useful genes and a good understanding of the host-pathogen interactions at the organismal and population levels. Thus, there is a continual need to understand what constitutes durable resistance to minimize the resurgence of new strains of pathogens. At the same time, we need to understand how diverse genes can be deployed in space or time to achieve durability at the cropping system level.

Using the diverse rice gene pool. Disease resistance breeding depends on available genetic variability in the vast collection of germplasm as a source of disease resistance. As of now, many major resistance genes have been identified that condition race-specific resistance against blast (35–37,45–47,78,88), bacterial blight (19,40,53,55,61,71,96,101), and more recently, rice tungro (6). There are more than 40 blast resistance genes (*Pi*) and 20 bacterial blight genes (*Xa*), and more are being identified. Of these, relatively few are actually used in commercial varieties on a large scale. Thus, the diversity of resistance genes available for use is much

greater than that being used in the field. Clearly, not all resistance genes are equally effective. Also, it is difficult to combine multiple genes based on phenotype alone. The situation is changing as more genes are physically tagged by molecular markers. Different gene combinations can now be created by monitoring the genes with markers in the breeding process (41).

Measuring and selecting the right phenotypes. The kinds of genes to be identified very much depend on the phenotypes being selected in a breeding program. Recognizing the drawback of selecting for absolute immunity (mostly due to race-specific resistance genes with strong effect), there was a shift in emphasis toward partial resistance in the 1980s. It was an important methodological change in the screening of germplasm and breeding lines for a range of diseases, including blast, bacterial blight, and tungro, in national screening nurseries. This approach in essence "relaxes" the selection to include more diverse genetic mechanisms in the advanced lines in a breeding program (12).

Creating the genetic stocks to monitor pathogen populations. Although not many resistance genes are actually used in commercial varieties, the diversity of resistance genes has been put to good use in developing differential varieties for pathogen characterization. For example, a large series of near-isogenic lines (NILs) for both bacterial blight resistance genes (72) and blast resistance genes (35,37,57) have been produced. For tungro virus, several NILs carrying resistance genes from diverse donors of traditional varieties (e.g., Utri Merah, TKM6) and wild rices (*O. rufipogon*) have been produced (6,7,82). These NILs have proven to be excellent experimental materials for differentiating pathogen races, evaluating effectiveness of individual resistance genes (55), and molecular cloning of disease resistance genes (86,91,96).

Understanding host-pathogen interactions. The development of NILs and molecular markers has provided the essential tools for understanding pathogen diversity and population structures that form the basis of deploying disease resistant varieties. The NILs carrying individual resistance genes provide an efficient means to detect changes in pathogen avirulence genes corresponding to specific resistance genes. This approach has been widely used in characterizing the bacterial blight (84,93) and blast pathogen populations (60,90,98) with the objective of determining the appropriate resistance genes to use and the impact of deployed genes on pathogen evolution. The ecological and population approach to disease resistance breeding was well received by researchers. Since the mid-1980s, a large amount of field and laboratory data have been accumulated on the pathogen populations of *Magnaporthe grisea* (14,18,50,54,60,90,99), *Xanthomo-*

nas oryzae pv. *oryzae* (1,4,29,51,70,84,92), and tungro viruses (3,5,8). For *M. grisea*, the pathogen population analysis has defined clonal populations, or lineages, of the pathogen as targets of breeding. A lineage is a group of pathogen genotypes that share a common DNA banding pattern that is inferred to be related by descent from a common ancestor. This led to the formulation of a breeding strategy where major genes are combined to exclude infection by the known pathogen lineages in a location (100). This "lineage-exclusion" approach is being pursued at Centro Internacional de Agricultura Tropical (CIAT) (30) and some research groups in Asia (9).

For bacterial blight, monitoring pathogen adaptation and molecular analysis of avirulence genes have provided useful clues as to which genes are more likely to be effective and durable in a particular environment (10,52,93). Such advanced understanding of pathogen population genetics and evolution is essential for effective utilization of host resistance genes. As knowledge of pathogen population accumulated, the research also gradually shifted from pathogen population characterization to experimenting with various deployment strategies.

Deployment Strategies Practiced in Rice

Sequential release of resistant varieties in time and space. Successful rice breeding programs regularly release new varieties adapted to various geographical locations. If a variety becomes susceptible to diseases, a new variety with different resistance genes is released to farmers. This replacement method is one way of dealing with multiple diseases and the changing needs of farmers and consumers. In practice, diverse donors with major genes and partial resistance are being utilized in breeding, that on average, 100,000 pedigrees are grown per year and screened for resistance (44). This system of screening and breeding has been successful in the tropical irrigated areas. Starting with the release of IR26 in 1973, nearly all released IRRI varieties had multiple resistance to blast, bacterial blight, grassy stunt, and later to tungro (43). Despite the gradual erosion of major gene resistance, some varieties have shown durable resistance in the tropical irrigated environment. For example, durable resistance to rice blast that is attributed to partial or quantitative resistance was observed in IR36 in irrigated tropical areas (13). For bacterial blight, deployment of a single resistance gene *Xa4* has proved to be effective for a long time. The gene has been incorporated in most of the IRRI varieties (16,38), and varieties with *Xa4* have been resistant to bacterial blight in the Philippines for 20 years even though compatible races are present (66,92). It has been suggested that varieties with the *Xa4*

gene also carry multiple minor genes for resistance, such that the apparent durability could be contributed by multiple genes with lesser effects (48).

Gene rotation based on pathogen race prediction was proposed for rice blast disease management (22). In this system, the emergence of new races was predicted to allow replacement of cultivars carrying a different resistance gene before a virulent race could increase to damaging levels. A modified single gene rotation scheme using two resistance genes at the same time was proposed to counter the rice blast epidemic in Korea in 1979–80. In addition to managing blast, a varietal rotation system based on planting different varieties in different seasons or localities was successfully implemented to control rice tungro in Indonesia (58), where rice varieties with different resistance genes against the insect vector green leafhopper were grown in different seasons. In another study, rotating different rice varieties was used as part of an integrated disease management scheme to reduce tungro; however, the success was attributed to synchronous planting schedules rather than varietal rotation (79).

Thus, sequential release of varieties over time and space is one form of diversifying varieties or resistance genes used in the field, but this strategy is valid only if the investment in developing a new variety is not out-balanced by the rapid loss of its usefulness. The system would also need to be supported by good race prediction and survey data.

Gene pyramiding. Based on an evolutionary risk assessment model, it has been argued that rice blast and bacterial blight can be managed by gene pyramiding, because it is unlikely that a sequence of multiple virulence mutations will occur in the same clonal lineage of the pathogen (59). However, a simulation model of blast evolution by Winterer et al. (94) showed that gene pyramiding is not an ideal strategy for deployment of blast resistance genes.

Combining multiple resistance genes in breeding lines is difficult by conventional breeding methods due to epistasis (masking effect of one gene over the others). Because many blast and bacterial blight resistance genes have been tagged by molecular markers, gene pyramiding is widely practiced in rice breeding (33,34,42,69,85). With marker-based selection, multiple genes can be identified in a single genotype (69). Thus, DNA marker technology has enabled the use of multiple resistance genes in a single variety, hence increasing the overall diversity of resistance genes used in the field. Using marker-aided selections, several varieties with multiple *Xa* genes have been produced by teams of researchers at Philippine Rice Research Institute (PhilRice), Philippines, Indonesian Agricultural Biotechnology and Genetic Resources Research Institute

(IABGRRI) in Indonesia, and Punjab Agricultural University in India (R. Tabien, M. Bustamam, and K. Singh, *personal communication*). Based on 2 to 3 years' evaluation in "hot spot" areas in farmers' fields, these lines showed resistance to bacterial blight under high disease pressure and out-yielded the check. Similarly, major genes for blast resistance (e.g., *Pi1*, *Pi2*, *Pi9*) have been accumulated in some elite lines by research teams in Indonesia and India, although the performance of these gene pyramids remains to be tested (M. Bustamam and R. Sridhar, *personal communication*). Past experience suggests that gene pyramids are most likely to be effective for controlling bacterial blight but less so for blast due to the high level of pathogenic variation exhibited by *M. grisea*. Alternative or complementary strategies are therefore needed for effective blast control.

Multilines and cultivar mixtures. A review of the literature indicates that reduction of blast can be achieved in multilines and cultivar mixtures as compared with pure stands (49,67). Based on a simulation model of pathogen evolution, Winterer et al. (94) argued that varietal mixture is the best deployment strategy for rice blast as compared with gene pyramids and gene rotation. The emergence of complex or "super" races has not been observed in fields using varietal mixtures or multilines (20,21,49).

Rice varietal mixtures are commonly used in traditional rice culture in Asia and Africa, such as in Madagascar and Indonesia (11). In Japan, multilines have been used successfully in commercial production (about 90,000 ha) by varying the composition of individual components according to the prevailing pathogen population (K. Ishizaki, *personal communication*). Chin and Husin (20) showed that a mixture containing 66% resistance component lines was adequate to control blast; whereas Koizumi (49) found that 75% resistance in a multiline was required to reduce severity to the level of control achieved by fungicide treatments.

In summary, there have been considerable activities in expanding the genetic basis for resistance in the field. Yet, other than the conventional release of new rice varieties with different resistance genes, most diversification methods have not been adopted or achieved the production scale needed by farmers. The recent interplanting experiments conducted in Yunnan demonstrated that simple methods coupled with strong extension support are critical in disseminating new approaches to disease management.

Varietal Diversification Experiments in Yunnan, China

In order to gain acceptance and adoption of any diversification strategies, positive results have to be demonstrated at the farm

level. Such a project was initiated in 1997 to explore the use of biodiversity to achieve sustainable pest management. The work was done using the “lighthouse concept” in which teams of researchers and extension workers worked together to solve a problem at a target location. Successful demonstration of principles and impact at the “lighthouse” site helps disseminate the knowledge and technologies to other places. One of the highlights of the project was the application of interplanting varieties to achieve blast control in Yunnan.

Due to the temperate climate and mountainous terrain, blast disease is widespread in Yunnan (Fig. 1). In this region, glutinous or sticky rice varieties have high sociocultural and market value because they are used for confections and other specialty dishes. However, they have low yield potential and are highly susceptible to blast. Before 1998, 98% of the rice fields in the study area were sown with monocultures of hybrid indica varieties Shanyou 22 and Shanyou 63. The glutinous varieties were planted in small areas because of their

vulnerability to blast. Thus, there are strong incentives for exploring methodologies to address a significant problem of economic interest to local farmers. We summarize below the process and approaches taken that are instructive to future implementation of diversification schemes in large scale.

Early exploratory experiments. In 1997, Yunnan Agricultural University and provincial extension workers approached farmers to implement a genetic diversification experiment in the field. Several diversification options were considered, including seed mixtures of two rice cultivars and planting different varieties in blocks within the same or adjacent fields. Farmers, however, were not receptive to these methods. On the contrary, many farmers had experience in using interplanting of varieties for disease control, but the scale was small with no fixed patterns. The situation presented an opportunity for researchers and extension workers to build upon farmers’ experience to develop the proper ratio and spatial arrangement of traditional glutinous rice and modern hybrid rice. The project

coordinated seed production and distribution to participating farmers and supported farmer training on the systematic evaluation and practice of methods of interplanting and its impact on diseases (Fig. 2).

The first experiment was set up in Bao Xiu, Shiping County, in small plots (0.07 ha) of participating farms in different villages. Traditional varieties and hybrid rice were planted in alternate strips (three to five rows); however, the result was not satisfactory and disease was severe among the susceptible varieties. At the same time, another varietal diversification experiment was conducted in Zhang Gui Zhai, in Shiping County. Based on farmers’ suggestions, one row of glutinous rice was planted for every four or six rows of hybrid rice (Fig. 3). Among the various combinations of varieties tested, the mixed planting of glutinous rice variety Huangkenuo or Zinuo with hybrid indica rice Shanyou 63 or Shanyou 22 significantly reduced the incidence and severity of rice blast disease and improved yield of the susceptible glutinous rice.

Scaling up. The success in Zhang Gui Zhai led to more demonstration areas and more participation by farmers. In 1998, the team tested this pattern in more fields and in another county, Jianshui. About 812 ha and more than 12,000 farm households were involved in the two counties. The positive results from the previous year prompted the Yunnan Provincial Department of Agriculture (PDA) to support technology extension of mixed planting to other counties in Hong He Prefecture. By 1999, more than 3,000 ha and 45,000 farm households were involved. The PDA and local government units committed additional resources to support training of local farmers from the different villages. Since then, farmers have adopted the basic patterns of interplanting 1 row of tall traditional rice varieties for every 4, 6, 8, or 10 rows of hybrid rice, depending on seed

Fig. 1. Highly blast-conducive environments in Yunnan, China. Experimental plots of different traditional varieties demonstrating high susceptibility to blast.

Fig. 2. Participation of farmers in experiments with different interplanting methods. A, Extension agents coordinating with farmers to ensure an adequate supply of seed of traditional varieties. B, Training courses and interviews conducted by provincial extension agents.

supply of the glutinous rice. In less than 5 years, the interplanting scheme has changed the landscape of the indica rice area in Hong He Prefecture (Fig. 4).

Results from the first 2 years confirmed the effectiveness of blast control and profitability of adopting mixed planting of glutinous and hybrid rice. Interplanting of the two varieties significantly reduced blast incidence by 94% on susceptible glutinous rice (102,103). The most successful varietal combination appears to be one row of glutinous rice varieties (either Huangkenuo or Zinuo) to four or six rows of hybrid rice varieties (Shanyou 63 or Shanyou 22). By the end of 2001, about 60% of the farming households in the indica rice area of Yunnan had adopted interplanting using different pair-wise combinations of hybrids, glutinous rice, or other traditional high-quality varieties.

Despite the practical success, the mechanisms involved are not completely understood. It is assumed that the different rice genotypes as well as the undulating canopy in rice fields created unfavorable environments for blast to develop. The height dif-

ference (20 cm) between the two varieties may have produced a microclimate less conducive to blast infection and pathogen sporulation in the canopy of the susceptible varieties (103). DNA fingerprinting of the fungus also indicated that the pathogen populations were more diverse in fields of interplanting than in monocultures of either hybrid or glutinous rice (Y. Zhu, H. Leung, T. W. Mew, and H. Chen, *unpublished data*). A diverse pathogen population may trigger induced resistance due to incompatible interactions between avirulent pathogen strains and host genotypes. Work is in progress to determine the relative importance of the agronomic and epidemiological factors in reducing disease and rice yield due to the competition of planting two varieties in the same field.

Impact promotes adoption. To understand the basis for the large-scale adoption of the diversification scheme, on-farm surveys were conducted in 2000 and 2001 (76). Two hundred sixty farm households (200 adopters and 60 nonadopters of the interplanting method) in 13 villages of Yunnan were interviewed. Results indicate

that the rapid adoption is driven by several factors.

Yield gains. Nearly 25 to 40% of the yield of monocropped glutinous rice is usually lost because of blast disease (102,103). The traditional varieties also suffer from lodging under windy conditions due to their weak stems and tall stature. On mixture farms, the yield of glutinous rice has increased by 1.72 t ha⁻¹ (Table 2). Nonadopters obtained less than 0.5 t ha⁻¹ of glutinous rice because the crop suffered from lodging at the milking stage. The combined yield of glutinous and hybrid rice was 11.08 t ha⁻¹ for adopters versus 9.57 t ha⁻¹ for nonadopters. Zhu et al. (102) estimated the ecological efficiency of mixed populations using the concept of land equivalent ratio (LER) and found that an average of 1.18 ha of monoculture cropland would be needed to produce the same amounts of glutinous rice as were produced in 1 ha of a mixture.

Reduced pesticide use. The reduction in blast disease leads to savings from reduced use of fungicides and the labor for spraying. The average number of sprays was

Fig. 3. A, Farmers interplanting glutinous and hybrid rice. B, Rice field showing the pattern of one row of glutinous rice for every four to six rows of hybrid rice.

Fig. 4. Changing rice landscape in Yunnan, China. A, Alternation of traditional (tall) and hybrid (short) rice is a common sight in the countryside of Yunnan. B, Panoramic view of a village (approximately 1,000 ha) that adopted the interplanting method.

three for the nonadopters compared with one for the adopters. Because of disease reduction, adopters spent \$1.50 ha⁻¹ for pesticides compared with \$4.42 ha⁻¹ spent by nonadopters, providing a saving of nearly \$3 ha⁻¹ (Table 3). There is also a positive effect on the health of farmers and the rice-growing environments.

Increase in farmers' income. Because of the increased yields and the high price of glutinous rice, the gross return realized by adopters is higher than that of the nonadopters. Adopters gained an additional \$104.53 ha⁻¹ at the 1998–99 price level (Table 4). Contrary to expectations that rice mixture requires more seed, adopters spent \$0.91 ha⁻¹ less for seed in 2000. This may be due to the more efficient use of seeds by farmers when they follow the straight-row planting of both glutinous and hybrid rice. On average, adopters saved about \$0.76 ha⁻¹ on seed expense.

Although additional labor costs are incurred for transplanting and harvesting, the savings from lower pesticide use and yield

gains from glutinous rice have more than offset the extra labor costs. Adopters also used more hired labor than before to enable the heads of household to engage in higher-income-generating off-farm employment. The net returns above cash costs obtained by adopters are \$92 ha⁻¹ higher than those of the nonadopters in 1998–99 (Table 4). The differential gain reached \$482 ha⁻¹ in 2000.

Conservation of traditional varieties. The application of genetic diversity by interplanting also allows farmers to bring many high-quality but disease-susceptible traditional varieties into active production (76). As the interplanted areas in Yunnan increased, so did the number of traditional varieties used in mixtures (104). Farmers began interplanting hybrid rice with 26 other traditional varieties that have good eating quality but are susceptible to blast. The number of traditional varieties brought back to production increased to 105 by 2002. We have quantified the shift in rice varietal diversity in farmers' fields by cal-

culating the diversity index based on the percentages of varieties (treated as genotypic frequencies) planted over 180,000 ha of rice land since 1997. On-farm genotypic diversity has increased from 0 (all hybrid rice) in 1997 to 0.35 in 2002 with 10 different traditional varieties occupying a substantial area (Fig. 5). Such baseline data will allow us to determine the relationship among genetic diversity, yield stability, and farmer income in the long term.

In summary, the technology of interplanting has spread from a mere 15 ha in an initial experiment involving two counties in 1997 to 812 ha in 1998 to 43,000 ha in 2000 (Fig. 6). By the end of 2001, about 70% of the farm households in the indica rice area of Yunnan had adopted mixed planting of rice varieties, and the area under mixture had expanded to 107,400 ha in 61 counties. In 2002, rice interplanting covered an area of 230,000 ha in 101 counties of Yunnan. Ten additional provinces in China have evaluated the diversification scheme and are prepared for large-scale implementation. Such rapid adoption can be attributed to the simplicity of the method and the systematic extension effort involving county and village officials, researchers, and extension workers (17). The extension network ensures not only that farmers are trained but also that seeds are available at planting time.

Beyond the Interplanting Experiments

The success achieved in Yunnan has generated considerable interest in varietal diversification and at the same time raised a number of questions. Can a similar approach of interplanting be extended to other crops? Will it work in different rice production environments and in different countries? It should be emphasized that the interplanting method is one form of diversification. While interplanting may be applicable to some other cropping systems, it is by no means a universal method to be practiced in all situations. Rather, it is the diversification concept that is of central interest to achieving sustainable crop productivity. The important lesson learned from the Yunnan experiments is that diversification can be effective and agronomically feasible provided that the implementation strategies are compatible with farmer cultural practices and that the results are economically attractive. In the long term, the strategy helps preserve traditional varieties with useful traits such as grain quality and adaptability. To generalize the diversification strategy, it is important to demonstrate its effectiveness in additional locations or cropping systems. We are currently evaluating various diversification approaches in different settings with the hope that each case study will reveal new insights on how diversity can benefit crop production.

Table 2. Mean yield of glutinous and hybrid rice by type of farmer^a, Yunnan Province, China, crop year 2000

Rice yield (t ha ⁻¹)	Adopters			Nonadopters	
	1998-99	2000	Difference	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	11.00	11.08	0.08 ^d	9.57	1.51 ^c

^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 $t = 3.365$, $P < 0.10$.

Table 3. Cost savings per hectare from reduction in pest pressure, Yunnan Province, China, crop year 2000, for farmers who did or did not adopt a diversification scheme

Item	Adopters	Nonadopters
Number of sprays	1	3
Cost of pesticides (US\$)	1.50	4.42
Labor for pesticide application (days)	0.63	0.76
Imputed cost of labor (US\$)	1.98	2.86
Total cost (US\$)	3.48	7.28
Financial benefit (US\$)	3.80	

Table 4. Costs and returns analysis (in US\$) by type of farmer^a and by year, Yunnan Province, China, crop year 2000

Item	Adopters		Nonadopters
	1998-99	2000	2000
Gross value of production	2,485.60	2,590.13	2,061.46
Cost of production			
Seeds			
Glutinous rice	0.14	0.06	0.14
Hybrid rice	8.03	7.20	7.88
Fertilizer	13.74	12.68	7.67
Pesticides	0.09	1.50	4.41
Hired labor	59.81	72.15	27.06
Net returns above cash costs	2,403.79	2,496.54	2,014.30

^a Farmers who did or did not adopt a diversification scheme.

Fig. 5. Proportion of area planted to different traditional varieties and index of genetic diversity, Yunnan, China. By 2002, at least 10 traditional varieties (names in inset) were in active production in the 180,000-ha area surveyed. Areas occupied by each variety are shown by the histogram, and the increase in genetic diversity index is shown by the line graph.

Rice blast in the uplands in Indonesia.

Rice blast is considered the most limiting constraint in upland rice production in Indonesia (87). Unlike the situation in Yunnan where the traditional varieties are mostly susceptible, the traditional upland varieties in Indonesia have good to moderate levels of blast resistance. In contrast, the modern varieties released to farmers succumb to blast within 2 to 3 years (A. Hasanuddin, M. Syam, E. Soenarjo, Suwarno, and Mukelar, *personal communication*). Farmers would like to plant modern varieties that give higher yield to raise their income yet retain the traditional varieties for consumption and as insurance against blast epidemics. If interplanting can protect the modern varieties against blast, it would help increase the productivity per area and sustain the use of traditional varieties.

Pilot field experiments are being conducted using a blast-resistant traditional variety Sirendah and a susceptible modern variety Cirata in disease hotspots in Lampung, Indonesia, to evaluate various interplanting schemes (Fig. 7). Preliminary observations suggest that leaf blast severity at maximum tillering stage is less in the interplanted plots (three and four rows of Cirata and Sirendah, respectively) relative to that of the pure stand. However, there is no significant reduction in neck blast (N. Castilla, W. Sabe Ardjasa, and A. Mukelar, *personal communication*). It appears that while interplanting may have a disease-reducing effect, a threshold level of resistance in the "susceptible" varieties is needed to benefit from the interplanting method. Work is in progress to introduce

Fig. 6. Rapid increase in rice area adopting the interplanting method between 1997 and 2002 in Yunnan, China. Areas covered by interplanting are indicated by the line graph and the increase in number of participating counties is shown by the histogram.

improved varieties with a higher level of blast resistance into the interplanting scheme.

Rice tungro viruses in the Philippines.

It is only in recent years that genetic resistance against tungro has been identified and incorporated into advanced breeding lines (6,82). Several sources of tungro virus resistance from traditional varieties and wild species have been incorporated

into elite genetic background. Furthermore, near-isogenic lines with and without resistance genes have been produced, making it possible to test mixture varieties. Experiments are being conducted in Iloilo in the Philippines where tungro is common and often reaches epidemic proportions. In this region, farmers prefer growing IR64, which has good eating and milling qualities. Thus, it is advantageous to retain as

many IR64-like varieties as possible in the field even though IR64 is highly susceptible to tungro.

The mixture deployed for tungro management in Iloilo involves mixing seeds in a 1:1 ratio of two rice varieties with similar plant types, eating quality, and maturity but differing resistance to the tungro virus (Fig. 8). Results from two crop seasons showed a 50% reduction in tungro incidence in the mixture relative to the pure stand. Farmers were receptive to the seed mixture and harvested the crop as a mixture and saved the seeds for next planting (R. Cabunagan and I. R. Choi, *personal communication*). The positive result prompted other farmers in the region to test seed mixtures in their own fields.

However, more performance data on the seed mixtures under high disease pressure are needed to determine if tungro resistance and yield gain are stable under stress.

Wheat stripe rust and broad bean fly and foliar disease in Yunnan. To extend the diversification concept to other crops, experiments have been conducted by Yunnan Agricultural University (YAU) to evaluate the interplanting method in wheat and broad bean. As part of a rice–wheat cropping system, wheat and broad bean are planted during winter on more than 250,000 ha in Yunnan. Wheat stripe rust caused by *Puccinia striiformis* is a major disease problem, causing yield losses as high as 15 to 20%. Broad bean is an impor-

tant cash crop planted in the same season as wheat, but bean yield often declines because of serious foliar disease caused by *Botrytis fabae*, and root and stem damage caused by bean fly maggots (*Ophiomyia phaseoli*). Researchers at YAU introduced intercropping by planting wheat in blocks of 1 × 20 m and planting two rows of broad bean between the blocks (Fig. 9). Results from five locations in Yunnan showed that the intercropping design reduced the incidence of wheat rust by 24%. Damage caused by bean fly maggots decreased by 19%. The intercrop maintained the same yield of wheat (4,791.5 kg/ha) as in monoculture (4,757.4 kg/ha) but gained an extra harvest of 656.6 kg/ha of broad bean.

Understanding and Incorporating Genetic Mechanisms

The above case studies demonstrate a diversity of “diversification schemes.” Our experience so far suggests that while diversification is generally sound, implementation of the specific methods has to be tailored to the practices of different cropping systems and characteristics unique to different pathosystems. For instance, in interplanting fields where blast was effectively controlled, we observed frequent occurrence of sheath blight and false smut. Thus, interplanting does not suppress all diseases. Clearly, the genetic composition of the varieties and epidemiological differences of the disease are important factors in determining the kind of diversification strategies most appropriate for certain production environments. The experiment in Indonesia will be informative, as it is designed to test whether resistant traditional varieties can be used to “protect” modern high-yielding varieties through interplanting. More case studies such as this are needed to develop diversification methods suitable for different cropping systems.

Good germplasm with respect to functionality is the foundation of any diversification strategy. By “good germplasm,” we do not necessarily mean improved modern varieties. Rather, germplasm with different attributes in quality, adaptability, and tolerance to different pests and diseases can be used in different combinations to achieve agronomic complementation. In Yunnan, the original pattern of interplanting traditional and hybrid varieties has been modified to include planting two traditional varieties with different agronomic attributes and eating qualities. Traditional varieties, as the result of years of natural and on-farm selection, are full of valuable traits. The challenge is learning how to determine or predict the performance of these traditional varieties such that they can be used by virtue of their agronomic complementarities with other improved germplasm.

Application of biodiversity therefore can be enhanced through a better understanding

Fig. 7. Interplanting experiment in Lampung, Indonesia, evaluating different mixture ratios of blast-susceptible (three rows of Cirata) and resistant (two rows of Sirendah) varieties. (Courtesy of N. Castilla and C. Vera Cruz)

Fig. 8. Rice tungro interplanting experiment in Iloilo, Philippines, showing tungro-susceptible IR64, tungro-resistant variety Matatag 9, and a 1:1 seed mixture of IR64 and Matatag 9. Note the severe tungro symptom in IR64. Disease incidence is considerably less in Matatag 9 and the 1:1 mixture. (Courtesy of R. Cabunagan and I. R. Choi)

of the genetic diversity of traditional and improved germplasm. With recent advances in genomics, new opportunities exist to associate genes with phenotypes on a genome-wide scale. In the context of applying biodiversity for disease management, we envision at least two applications in the near future. First, germplasm with diverse genetic resistance mechanisms can be produced in a more efficient way. Genes can be selected to confer different mechanisms of resistance. Liu et al. (56) recently reported the application of candidate defense genes to develop blast-resistant breeding lines with resistance to diverse pathogen populations. The ability to precisely select for specific genotypes will yield valuable germplasm as ingredients for any diversification program. Second, we foresee the possibility of functional prediction of agronomic complementation by examining a large number of genes in the germplasm pool. In this way, traditional varieties can be preselected for use in different diversification schemes. To test this hypothesis, we are applying molecular markers to determine the genetic distance between modern and traditional varieties in Yunnan and to learn if there is any positive correlation between genetic distance and field performance observed in interplanting experiments.

Future Perspectives

We have reviewed the evolving research strategy that emphasizes the use of genetic diversity as a means for managing diseases in a sustainable manner. By examining the research “road map,” we gain clarity in the emerging needs and also new possibilities in solving rice pathology problems. The survey of Savary et al. (80,81) indicates the importance of maintaining genetic resistance to the major diseases of high epidemic potential. Furthermore, the relatively low incidence of diseases in the large area of unfavorable environments is largely due to low productivity. As we seek to improve productivity in these areas, disease problems will become more prominent. Thus, there should be no complacency in developing better germplasm and varieties with a broad spectrum of disease resistance. Yet, for some areas, increased production alone does not necessarily bring about high income for the farming community because of depressed rice prices. Farmers prefer growing high-value agricultural products—including high-quality and specialty rice that command a higher price in the market. Thus, a production system that allows high productivity per unit land area through better crop protection and coexistence of traditional and modern varieties will be well accepted by farmers.

Because of the evolving pathogens and changing cropping systems, maintaining plant health requires anticipatory and proactive strategies. Genetic diversity is the “currency” to manage the “arms race”

between the pathogen and host genotypes introduced by breeding (Fig. 10). At the genotypic level, broad-spectrum resistance for major and minor diseases using different genetic mechanisms is important. With the rice genome sequence available (31,97), we have the capacity to identify a large pool of resistance genes and defense-response genes that encode multiple mechanisms of resistance. Knowing how these genes function will undoubtedly improve our ability to use them effectively. At the cropping system level, we will need to go beyond the deployment of resistance genes in a variety but consider using a large suite of agronomic traits that together provide enhanced resilience to a wide range of stresses.

Traditional varieties are often seen only as “donors” of useful genes, and little attention has been given to their utility in a high productivity system. Our experience in Yunnan indicates that capitalizing on this valuable resource does not necessarily mean “converting” these traditional varieties into modern genotypes by breeding. In many situations, traditional varieties are highly valued for a variety of reasons—esthetic, eating qualities, ceremonial needs, and so on. Farmers are interested in growing them to meet such needs and to receive higher return in the marketplace. Thus, ability to grow these varieties without altering certain traits should be considered as a complementary strategy in modern rice production. The Yunnan exper-

Fig. 9. Intercropping of wheat and broad bean to reduce diseases and insect damage in Yunnan, China. A, Two rows of broad bean are planted between 1-meter strips of wheat. B, Stripe rust of wheat. C, *Botrytis* foliar disease of broad bean.

Fig. 10. Roles of genetic diversity in modern agriculture and options to increase genetic diversity in achieving sustainability.

iment indicates a successful case where traditional varieties can be co-cultivated in a highly productive system. Extension of such a system, or a variation of it, can provide strong incentive for the conservation of traditional varieties at local communities, contributing to the long-term preservation of genetic resources.

Since the Green Revolution, a major objective of rice disease control has been preventing yield loss. Although this objective has not changed, there is the added impetus that crop protection should be conducted in the context of improving the livelihood of rural poor and preserving limited natural resources. We have shown case studies where management of diseases through the use of genetic diversity can contribute to the development of broad-spectrum resistance, generation of income, and conservation of genetic resources. The scientific bases for implementing these approaches are much stronger now than decades ago. The challenge for the future lies in merging new science with on-farm practice to bring about benefits to the local community.

Acknowledgments

We thank Roger Cabunagan, Il-Ryong Choi, and Nancy Castilla for sharing unpublished data, Mahabub Hossain for advice in the impact survey studies, and Emerlito Borromeo and Vivay Salazar for technical assistance. We thank many collaborators in China, India, Indonesia, and the Philippines for the partnership to identify resistance genes and apply them in breeding programs and farmers' fields. Collaboration with colleagues at universities in Japan, Korea, and the United States has been instrumental in developing the knowledge and tools. We are grateful to the Asian Development Bank and Yunnan Provincial Department of Agriculture for supporting the work in Yunnan.

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