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Opportunities for Global Rice Research in a Changing World

Global Futures for Agriculture Project

IRRI
International Rice Research Institute

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Compiled by
Axel Tonini
Ellanie Cabrera

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IRRI
INTERNATIONAL RICE RESEARCH INSTITUTE

The International Rice Research Institute (IRRI) was established in 1960 by the Ford and Rockefeller Foundations with the help and approval of the Government of the Philippines. Today, IRRI is one of the 15 nonprofit international research centers supported by the Consultative Group on International Agricultural Research (CGIAR – www.cgiar.org).

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The responsibility for this publication rests with the International Rice Research Institute.

Mailing address: DAPO Box 7777, Metro Manila, Philippines
Phone: +63 (2) 580-5600
Fax: +63 (2) 580-5699
Email: irri@cgiar.org
Web: www.irri.org.
Rice Knowledge Bank: www.knowledgebank.irri.org
Courier address: Suite 1009, Security Bank Center
6776 Ayala Avenue, Makati City, Philippines
Tel. +63 (2) 891-1236, 891-1174, 891-1258, 891-1303

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Opportunities for Global Rice Research in a Changing World

Introduction

Several factors threaten sustainable agricultural production growth, particularly in developing countries. Some of the main variables that affect the future of agricultural production are rising nighttime temperature, higher incidence of extreme weather, declining water table, declining agricultural land, rising input prices, land degradation, and other environmental concerns. Therefore, it is essential to increase investment in agricultural research and infrastructure development to improve agricultural productivity in a sustainable manner to meet the nutritional needs of an increasing population.

The global demand for cereals is expected to rise in the future as countries become wealthier and the population rises, particularly in Africa and Asia. The same is true for rice, whose consumption is expected to exceed production in many Middle Eastern, African, and Latin American countries. Mohanty (2009) estimated that global rice consumption in rough equivalent will increase by 90 million tons by 2020. Per capita rice consumption is expected to be globally stable. The decline in Asian countries, where economic growth diverts consumption from rice to other high-value food products, is more or less offset by rising per capita consumption in the rest of the world. Currently, yields are stagnating in the major rice-producing areas of Asia, which suggests a lack of genetic gain in yield potential[1] in rice improvement programs. During the 1960s, the yield potential of the irrigated rice crop increased from 6 to 10 t/ha in the tropics. This was accomplished at the International Rice Research Institute (IRRI) primarily by reducing plant height through the incorporation of a recessive gene, *sd1*, for short stature from Chinese variety Dee-geo-woo-gen. Now, modern high-yielding semidwarf varieties produce about 12 t of grain per hectare (Virk et al 2004).

Rice varieties with a yield advantage of about 20% over widely grown varieties under tropical conditions must be developed to achieve a target yield able to cope with climate change. The need to increase the cultivated area under rice is becoming a problem in most countries and area is still decreasing as a result of urbanization and industrialization. To achieve yield potential, the crop must be optimally supplied with water and nutrients and completely protected against weeds, pests, diseases, and other factors that may reduce growth. Such conditions are rarely achieved under field conditions, nor is it likely to be cost-effective for farmers to strive for such perfection in management. Instead, understanding site yield potential and its normal year-to-year variation can help in identifying management options and input requirements that combine to reduce the size of the exploitable yield gap while maintaining profitable and highly efficient production practices.

Rice scientists at IRRI have established that shifting the yield frontier in rice is an important research goal in order to meet the continuously increasing demand for rice produced from less land, less water, less labor, and fewer chemical inputs, which leads to the development of hybrid rice technology for the tropics. Hybrid rice has particularly good potential to improve the food security of poor countries where arable land is scarce, populations are expanding, and labor is cheap.

This report aims to shed light on the opportunities for global rice research in a changing world. From Section 1.2 to Section 1.4, the report describes the most important changes in rice productivity in the last decades, highlighting why increasing rice productivity is still a vital objective and the pressing concerns that need to be examined. Section 1.5 focuses on the breeding characteristics of rice that focus on shifting the yield frontier and improving yield sustainability. Yield sustainability is tackled by addressing biotic and abiotic stresses. Directed-seeded rice, improved management strategies, grain quality, malnutrition, and preparations for handling climate change close this report.

The significance of rice

Rice is the most important food crop of the developing world. It is the staple food of more than half of the world's population, for which about 90% of rice is grown by more than 200 million small rice farmers with landholdings of less than 1 hectare. Harvested from 159 million hectares annually, rice has twice the value of production in the developing world as any other food crop: more than US$150 billion per year. One-fifth of the world's population, more than 1 billion people, depends on rice cultivation for livelihood.

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[1] Yield potential is defined as the yield of a variety when grown in environments to which it is most adapted, with nutrients and water not limiting and pests and diseases and other stresses effectively controlled.

Worldwide, more than 3.5 billion people depend on rice for more than 20% of their daily calories. For the extreme poor (earning less than $1.25/day), rice accounts for nearly half of their food expenditures and a fifth of total household expenditures. This group alone annually spends the equivalent of $62 billion (PPP) for rice. Nearly 560 million people living on less than $1.25 (purchasing power parity, PPP) per day are in rice-producing areas, far more than for any other crop (Fig. 1).

Poverty-line numbers indicate that, after the Green Revolution (GR), the number of Asian people living in $1/day poverty declined remarkably. The number of poor decreased by about 27% between 1975 and 1995 despite a 60% population growth over the same period (Hazell 2010). Most poor people in the region that left the poverty line were rural, deriving important sources of their income from agriculture-related activities. The GR was certainly one of the major forces that contributed to the livelihoods of the poor in the region. Since 1966, when the first high-yielding varieties (HYVs) of rice were released, rice area has improved only marginally, from 126 to 152 million hectares (about 18%), whereas the average paddy yield has augmented by 86%, moving from 2.1 to 3.9 tons per hectare. World production increased by 133% from 257 million tons in 1966 to 600 million tons in 2000. In 2000, the average per capita food grain availability was 20% higher than in the 1960s. Food security improved considerably, thus enhancing political stability, investments in education, infrastructure development, and industrialization (Khush and Virk 2005). During 1965-1990, the daily calorie supply in relation to the requirement improved from 81% to 120% in Indonesia, from 86% to 110% in China, from 82% to 99% in the Philippines, and from 89% to 94% in India. The increase in per capita availability of rice and the decrease in the cost of production per ton of output contributed to a decline in the real price of rice, in both domestic and international markets (Khush and Virk 2005).

Rice consumption can be very high, exceeding 100 kg per capita annually in many Asian countries. A large part of the total dietary energy consumption comes from rice in Asia, where about 70% of the world's poor live (Dawe 2002). As shown in Figure 2, rice provides more than 50% of the caloric supply for many low- and middle-income Asian economies.

In Southeast Asia (Cambodia, Laos, and Vietnam), the share of rice in total dietary consumption is above 60%, whereas in Bangladesh it reaches 71% (FAOSTAT 2010). In sub-Saharan Africa, urban dwellers that only a few decades ago rarely ate rice now consume it daily. Per capita consumption has doubled since 1970 to 27 kg. In South America, average per capita consumption of rice is 45 kg. In the Caribbean, it has already surpassed 70 kg.

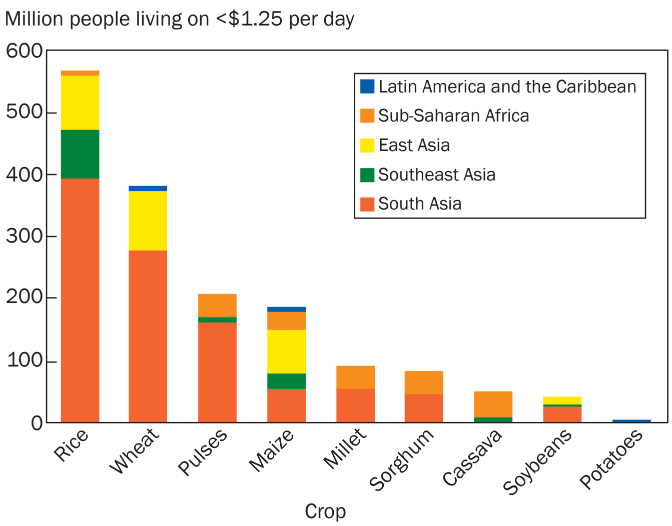

Fig. 1. Number of people below the poverty line ($1.25 per day)[2], 2005 data. Source: IRRI (2010a).

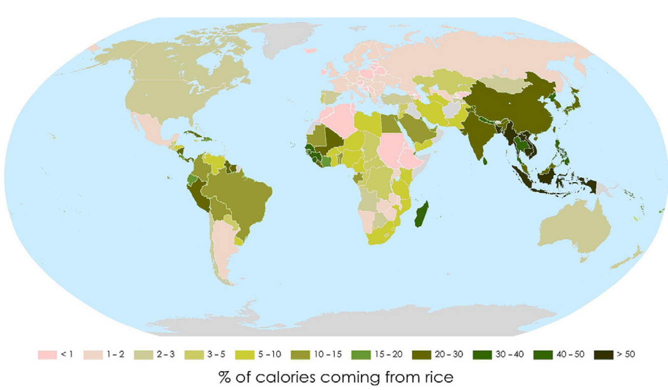

Fig. 2. Percentage share of calories consumed coming from rice. Source: IRRI (2010a).

The trend in rice yield

World paddy rice production was about 225 million tons when the first modern rice varieties were developed in the early 1960s. Over the years, world paddy rice production has increased to 680 million tons through the application of principles of Mendelian genetics and conventional plant breeding and the adoption of modern HYVs, coupled with improved management practices. Despite this remarkable achievement, the yield potential of modern rice varieties has been stagnant at 10 tons per hectare since the release of IR8 in 1966. The development of F_1 hybrids[3] has increased yield potential by 5–10% under tropical conditions. The annual rate of yield increase from 1960 to 2010 has been only 52.4 kg per hectare (Fig. 3).

Trends in world rice prices and production appear in Figure 4 for the period 1961-2009. From 1965 to 1981, during the GR period, prices started to fluctuate more in relation to the

[2] Numbers are based on areas more than 10% covered by the dominant crop. Some areas have more than one dominant crop and thus overlap.

[3] F_1 hybrid is a term used in genetics and selective breeding. F_1 stands for Filial 1, the first filial generation of seeds/plants or animal offspring resulting from a cross mating of distinctly different parental types.

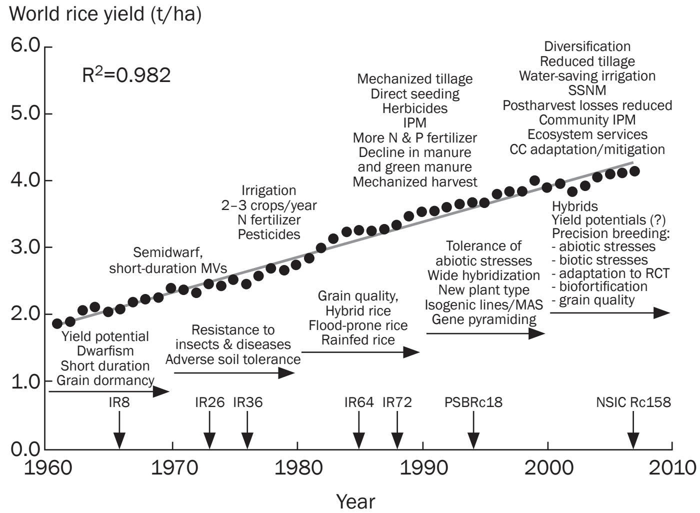

Fig. 3. Annual rate of yield increase in rice (1960-2010).
Source: IRRI (2010a).

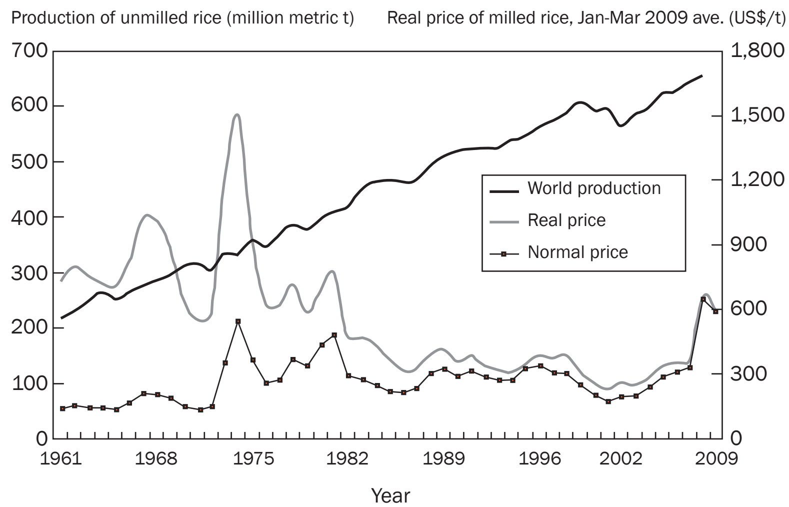

Fig. 4. Trends in world rice production and price, 1961-2009.
Source: World Bank (Pink Sheet) (2010).

introduction of modern fertilizer-responsive varieties and the world food crisis of 1973-75, with two price peaks in 1974 and 1981. From 1981 to 1986, world rice prices started to suddenly plunge, declining by 60% in 5 years. One of the causes of this price decline was the self-sufficiency that Indonesia, one of the largest rice importers, reached in 1984 (Dawe 2002). Indonesian rice production from 1981 to 1986 increased by 22%. During the same period, economic growth also fostered production increases in other Asian countries such as China, India, and Vietnam, with a remarkable impact on world prices. This period introduced a post-GR regime with more stable prices from 1986 to 1998. Prices became more volatile in 2002-09 in relation to the 2008 world food crisis. The price of rice adjusted for inflation is now about 50% lower than in the mid-1960s.

The remarkable price plunge registered between 1981 and 1986 was accompanied by an increase in per capita production of about 10%, reaching 155 kg paddy per capita. This same level has been maintained up to now. Although the increase in per capita production from 1981 to 1986 was exceptional, per capita production has been rising since the 1960s. The decline in food prices during that time benefited the urban poor and rural landless, who are not directly involved in food production but who spend more than one-half of their income on food grains. As net consumers of grain, small and marginal farmers, who are dominant rice producers in most Asian countries, have also benefited from the downward trend in the real prices of rice.

For most of the Asian countries in that period, the income elasticity of demand was still positive and the increased production had to face not only population growth but also income growth. As soon as the Asian economy improved, per capita incomes increased, shifting the income elasticity of demand from positive to close to zero and in several cases even to negative. So, in some of the most advanced economies, per capita rice consumption declined (i.e., Japan, South Korea, Malaysia, and

Thailand), whereas, in other countries (i.e., China, Indonesia, and the Philippines), per capita rice consumption remained rather stable.

In the past, when production was lagging behind consumption, area growth helped to reduce the gap (Fig. 5). However, this trend cannot continue in the future as area growth is expected to decline and even decline in absolute numbers as competition will increase for rice area from urbanization and other nonagricultural uses.

Global rice consumption remains strong because of increased population as well as economic growth in the regions. Consumption increased by 12% from 1998-99 to 2008-09, moving from 388 million tons to 436 million tons. Per capita consumption has been globally stable in the last 20 years. However, different patterns can be observed, depending on the extent of income growth. In countries characterized by high income such as South Korea, Japan, and Taiwan, per capita consumption of rice declined by about 40% in the last 20 years. In countries with moderate income such as China and Thailand, per capita consumption declined by 7 and 9 kg during 1990-2005, respectively.

In India, per capita consumption also declined after rising for two decades and, between 2004 and 2008, it increased by 6%. In Vietnam, the decline in per capita consumption has been larger in urban areas than in rural areas. In the last 15 years, per capita consumption went down by 21% in urban areas and by 10% in rural areas. Contrasting with this trend is the Philippines, where per capita consumption is continually growing thanks to income increases in both urban and rural areas. Total consumption in the last decade increased by 64% and this increased the dependency on the international market. Nowadays, the Philippines is the world's largest importer. It is expected that, in the future, per capita consumption will decline in most Asian countries due to increasing income and shifting consumption habits from staple food to more products with high value added. In Africa, the United States, Latin America, and the European Union, where rice is not a staple, per capita consumption is continually growing (Mohanty et al 2010). In West and Central Africa, demand for rice is increasing by 6% per year (Bouman et al 2007).

Mohanty et al (2010) estimated global rice demand using the population projections of the United Nations and income projections from the Food and Agricultural Policy Research Institute (FAPRI). Global rice demand is estimated to grow by 13% and 26% by 2020 and 2035, respectively, compared with the 2010 level of 439 million tons of milled rice (Fig. 6). As population growth will decline and people start to diversify their diets to food other than rice, the rate of growth of global rice production will decline. The largest increase in total global consumption will come from Asia, where consumption is expected to increase by 20% in 2035 from the 388 million tons consumed in 2010. Over the next 25 years, rice consumption is expected to increase in Africa and in America by 130% and 33%, respectively.

Mohanty et al (2010) simulated the yield growth rate necessary to keep the rice price constant at 2005-08 world reference prices. This results in a yield growth rate of 15% in the next 10 years in order to maintain prices at $300 per ton, which translates into a 6.3% increase in rice yield as compared with the baseline over the same period (Fig. 7). As a consequence of lower rice prices, land allocation is also affected with a diversion to other productive uses. Per capita consumption because of lower prices will tend to increase as well as trade-decreasing price volatility.

Annual growth in cereal crop area, yield, and production in Asian regions is represented in Table 1. Growth in cereal production declined in developing Asian countries from 3.10% per year to 1.68% per year from 1967-82 to the 1995-2009 period. Rice yield growth in Asia continually declined from 2.27% per year in the first subperiod to 0.95% in the last subperiod. Declines in rice yield growth were remarkable in East and Southeast Asia, whereas, for southern Asia, which was considered a slow

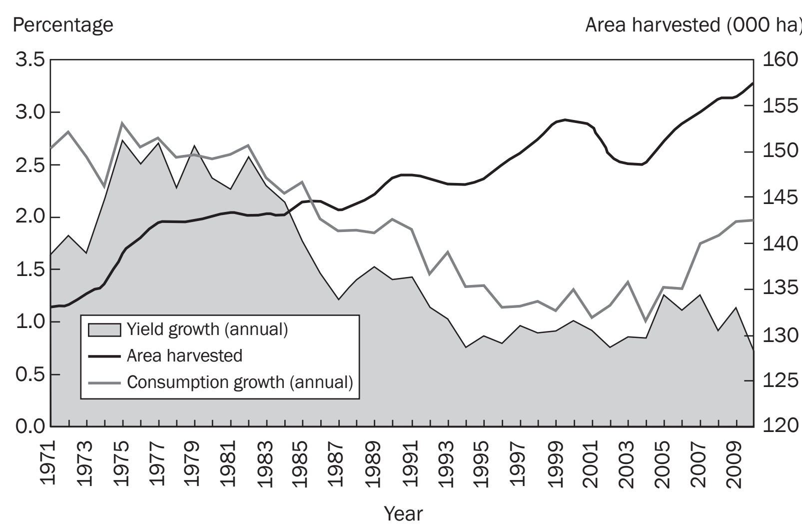

Fig. 5. Global rice food security: area vs. yield growth (10-year moving average). Source: Production, Supply and Distribution Online (USDA, Foreign Agricultural Services). More details can be found at www.fas.usda.gov/psdonline/.

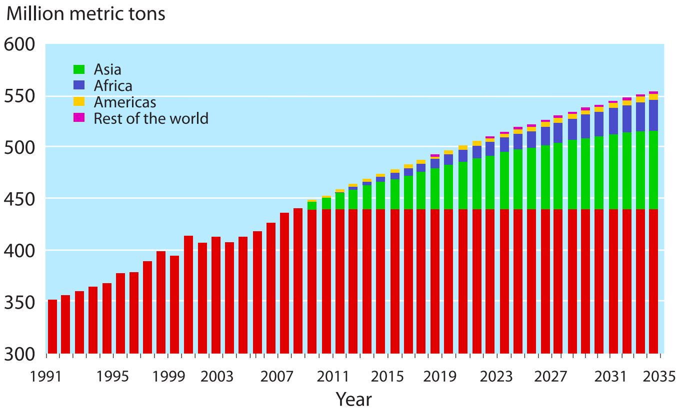

Fig. 6. Global rice production increases necessary to match consumption by 2035. Source: IRRI (2010a).

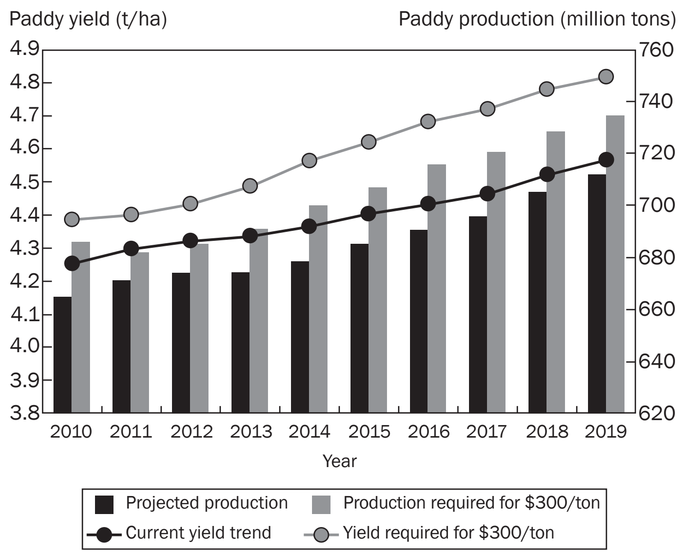

Fig. 7. Yield and production needed to keep the rice price at an affordable level of $300 per ton. Source: IRRI (2010a).

adopter of HYVs, yield growth increased from 1.25% in 1967-82 to 2.62% in 1982-95 and then declined to 1.21% in 1995-2009.

Figure 8 displays annual growth in rice yields for relevant Asian subregions. In the first phase of the GR in 1967-82, higher yields and profitability pushed farmers to acquire more land for rice and wheat at the expense of other crops. The growth rates were particularly favorable in the so-called breadbasket areas (e.g., Punjab and Haryana in India and Central Luzon in the Philippines), where the GR was most effective (Hazell 2010).

What are the pressing concerns?

The most important challenges are to guarantee a sufficient rice supply in response to the growing and urbanizing population as well as to alleviate poverty. For every 1 billion people added to the world's population, 100 million tons more of rice (paddy) need to be produced annually—with less land, less water, and less labor, in more efficient, environmentally friendly production systems that are more resilient to climate change and that also contribute less to greenhouse gas emissions. Recently,

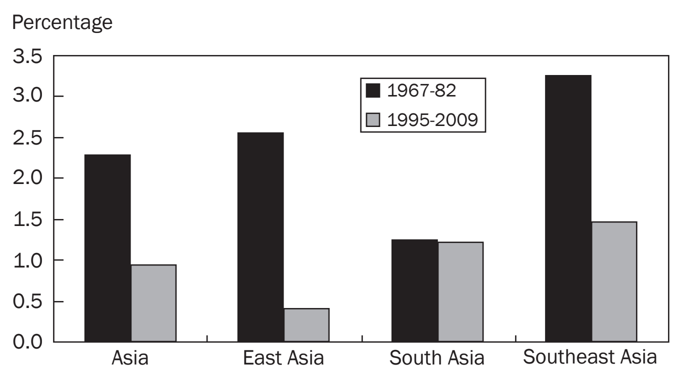

Fig. 8. Annual growth in rice yields, 1967-82 vs. 1995-2009. Source: FAOSTAT (2010).

Table 1. Annual growth for rice and all cereals in crop area, yield, and production by Asian regions, 1967-2009.

Crop and region	1967-82			1982-95			1995-2009		
	Area	Yield	Prod.	Area	Yield	Prod.	Area	Yield	Prod.
Rice									
Asia	0.51	2.27	2.79	0.46	1.58	2.05	0.50	0.95	1.46
East Asia[a]	0.29	2.56	2.86	−0.62	1.49	0.87	−0.38	0.67	0.28
South Asia[b]	0.45	1.25	1.71	0.63	2.62	3.27	0.44	1.21	1.66
Southeast Asia[c]	0.87	3.25	4.14	1.20	1.55	2.77	1.30	1.48	2.81
All cereals									
Asia	0.30	2.79	3.10	0.70	1.90	2.61	0.18	1.50	1.68
Eastern Asia	−0.25	3.48	3.22	−0.17	2.16	1.98	−0.16	1.12	0.96
South Asia	0.53	2.00	2.54	0.03	3.08	3.11	0.20	1.52	1.73
Southeast Asia	0.96	3.14	4.13	1.21	1.73	2.96	1.25	1.84	3.11

[a]East Asia comprises China, Japan, Korea, and Mongolia. [b]South Asia comprises Afghanistan, Bangladesh, Bhutan, India, Iran, Maldives, Nepal, Pakistan, and Sri Lanka. [c]Southeast Asia comprises Brunei Darussalam, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, Timor-Leste, and Vietnam.
Source: FAOSTAT (2010).

the concomitant decline in yield growth rates together with unfavorable weather conditions and increasing demand from economic and population growth lowered world rice stocks to unprecedented levels,[4] with escalating pressure on prices. The increase in biofuel crops sidetracked land to rice, thus increasing rice prices. From November 2007 to May 2008, rice prices tripled as a result of protectionist measures adopted in the major exporting countries (Mohanty et al 2010). These issues showed the need to examine new strategies to face the expected incoming imbalance between supply and demand. In addition, the challenge is not only to produce more rice for the poor but also to keep its price at an affordable level for the well-being of the poor. However, lower prices may negatively impact farmer profitability, which is why it is necessary to pursue a decrease in the cost of producing rice (Bouman et al 2007). This is even more important when we consider small rice producers that could not benefit from the adoption of new modern rice varieties. Poverty is still significant in the remote upland areas of Laos, Nepal, Vietnam, northeastern India, and sub-Saharan Africa. However, improving rice productivity may be the first milestone in making land available to more profitable crops and favoring labor outflow from agriculture.

Yield growth has fallen, partially as a result of the decline in investment in productivity research since the early 1990s, from 2.2% during 1970-90 to less than 0.8% in the 1990s and 2000s. Rice area in the major producing countries has been decreasing because of the conversion of land for other purposes. Competition for water is becoming increasingly fierce. By 2025, 15–20 million ha of irrigated rice will suffer some degree of water scarcity (Tuong and Bouman 2003), which results from competing water uses and climate change, and requires rethinking of current management paradigms. Water stresses are likely to transfer rice production to areas with more abundant water, concentrate production there, and require aerobic soil conditions in water-scarce areas. The empirical evidence shows that rice under nonflooded permanent conditions may be more subject to pests, diseases, and weed growth. For rainfed environments, one of the challenges is to minimize the negative consequences of land intensification where tests have been showing emerging nutrient deficiencies.

In northwestern India, declining groundwater levels pose a serious threat to one of the world's most important grain baskets. In fact, rice systems draw much of their ecological resilience from intensive water use and new solutions need to be found for water-scarce conditions. Fewer hands are available for farming as young people prefer to look for jobs outside the agricultural sector. Although there is still scope for expanding rice area in the three regions, conservation of natural ecosystems must remain a high priority. Increasing rice yields on existing land must remain the primary strategy for increasing production. Particularly for African and South American farmers, another challenge will be to make greater use of largely unused lowlands while preserving their ecosystem services and taking the pressure off of fragile upland systems.

Rapid economic growth in large countries, such as China and India, has heightened demand for cereals, for both consumption and livestock production, and this has pushed up the price of cereals in general. Economic growth is often accompanied by diversification of food demand, which creates opportunities for diversification of rice-based systems to include higher-value crops and livestock, but also reduces the amount of land available for rice. The rice-related tensions that developing countries face are growing more complex as their economies grow: between poor rice farmers and poor consumers, between small-scale and large-scale rice-based farms, between rice and more lucrative/cash crops, between edible crops and biofuels, between crops and other land uses, and between crops and other water uses. Prices of fertilizer are bound to stay high, especially for phosphorus, given the current status of known reserves.

As a consequence of economic growth, current rice cultivation areas are likely to be lost to urban expansion, land conversion to biofuels, and diversification into other agricultural products. This all means that sufficient production to meet growing future demand will have to come from smaller and smaller areas, particularly if diversification is to be possible while keeping rice prices affordable to poor consumers. In turn, this adds urgency to the need to improve productivity.

Global climate change has potentially grave consequences for rice production and, consequently, global food security. Land-use systems in most developing countries are highly vulnerable to climate change and have little capacity to cope with its impacts. Conditions for rice farming will deteriorate in many areas, through water shortages, low water quality, thermal stress, sea-level rise, floods, and more intense tropical cyclones. Moreover, flooded intensively managed rice systems release large amounts of methane, but also sequester carbon in soil organic matter, whereas more diversified rice-based cropping systems release less methane, but more nitrous oxide and carbon dioxide. Africa is expected to be very vulnerable to erratic weather patterns arising from climate change, but most disconcerting is that more than half of the growth in Asian rice production over the past decades came from the "delta countries," such as Vietnam and Bangladesh—precisely the countries most vulnerable to sea-level rise and climatic extremes. Many unique ecosystem services in wetland rice culture are now under threat from increasing water scarcity, further aggravated by climate change.

In order to solve these problems, rice production needs to increase through growth in yield rather than in harvested area. Rice area is now at its historic high and it is unrealistic to foster rice production with increases in area. Therefore, a call for a second GR is launched with the need to specify for global rice research a new strategy to pursue. What strategy needs to be pursued remains a challenging question. It is no doubt important to develop and support the competitiveness of rice production

[4] According to Mohanty et al (2010), global rice stocks declined from 147 million tons in 2001 to 82 million tons in 2008, which is equivalent to a decline from a 135-day supply to a 70-day supply.

in developing countries by a further shift in the yield frontier, stabilizing yields and making resource use more efficient, taking into account that climate change weakens the traditional distinction between favorable and unfavorable (marginal) environments. Nowadays, even favorable environments may be severely affected by drought, heat, salinity, and submergence.

Enhancing rice productivity

Recent advances in modern plant breeding methodologies, molecular genetics, genomics, marker-assisted selection (MAS), and transgenics offer new opportunities to meet these challenges.[5] Some of these advances include (1) a dense molecular map consisting of more than 4,000 DNA markers; (2) many important genes/quantitative trait loci (QTLs)[6] governing abiotic and biotic stresses tagged with molecular markers;[7] (3) MAS practiced for resistance to submergence, salinity, bacterial blight (BB), blast, brown planthopper (BPH), etc.; (4) transfer of genes for resistance to BPH, BB, blast, tungro, etc., from wild species across crossability barriers; (5) extensive synteny[8] with genomes of other cereals; (6) ease in genetic transformation and production of transgenics for tolerance of abiotic and biotic stresses and improved nutritional quality; (7) a large set of T-DNA insertion lines (>100,000), 60,000 deletion mutants, and YAC, BAC, and EST libraries;[9] (8) high-throughput methods/materials (gene chips) for gene discovery and gene expression analysis; (9) genome sequences of both indica and japonica;[10] and (10) BAC libraries of 10 genome types of *Oryza* species.

Shifting the yield frontier

Several strategies have been proposed to break the yield ceiling in rice. Plant physiologists proposed increased photosynthetic efficiency and sink size[11] as possible approaches to increase yield potential (Evans 1973, Yoshida 1972, Yoshida et al 1972). Some of the strategies, discussed afterward, include

a. Breeding new ideotypes for higher yield
b. Developing hybrids with higher yield potential
c. Introgressing yield-enhancing loci (wild species alleles)
d. Pyramiding genes/QTLs for agronomic traits
e. Developing C_4 rice

Describing the traits for yield potential. The concept of breeding for ideotypes "based on plant architecture" was given as early as 1968 by Donald for increasing the yield of cereals. Since then, several scientists have suggested breeding for high yield based on "ideotypes." Yield is a function of total dry matter (biomass) and harvest index.[12] Modern HYVs have a harvest index of 0.5 and a total biomass of about 20 t/ha under optimal conditions. By raising biomass to about 22 t/ha and harvest index to 0.55, it should be possible to obtain yield of more than 12 t/ha. Breeding a new ideotype, dubbed the "new plant type, NPT," began at IRRI in 1989. The suggested modifications of HYV plant architecture included

a. A reduction in tiller number (5–6),
b. An increase in the number of grains per panicle,
c. A deeper root system,
d. Thicker and dark green leaves, and
e. Straw stiffness (Table 2).

This ideotype became the NPT highlighted in IRRI's strategic plan (IRRI 1989). The goal was to develop an NPT with 30–50% higher yield potential than the existing semidwarf varieties in tropical environments during the dry season (Peng et al 1994).

Genetic donors for the target traits were identified in "bulu" or javanica germplasm mainly from Indonesia (Table 3). This

Table 2. Characteristics of the new plant type (NPT) for rice.

Agronomic traits	Capacity
Tillering ability	Low, with 3–4 panicles per plant when direct seeded No unproductive tillers
Number of grains per panicle	200–250
Plant height (cm)	90–100
Stem	Sturdy
Root system	Vigorous
Resistance to diseases and insects	Multiple
Growth duration (days)	110–130
Harvest index	0.6
Potential grain yield (t/ha)	13–15

Source: IRRI (1989).

[5] *Molecular genetics* is the field of biology and genetics that studies the structure and function of genes at a molecular level, and that studies how the genes are transferred from generation to generation. *Genomics* uses intensive efforts to determine the entire DNA sequence of organisms and to fine-scale genetic mapping efforts. *MAS* is a process whereby a marker (morphological, biochemical, or one based on DNA/RNA variation) is used for indirect selection of a genetic determinant or determinants of a trait of interest. A *transgenic* is an organism that has had genes from another organism put into its genome through recombinant DNA techniques.

[6] Quantitative trait loci (QTLs) are stretches of DNA containing or linked to the genes that underlie a quantitative trait.

[7] A molecular marker/genetic marker is a fragment of DNA sequence that is associated with a part of the genome.

[8] Synteny describes the physical co-localization of genetic loci on the same chromosome within an individual or species.

[9] YAC = yeast artificial chromosome; BAC = bacterial artificial chromosome; EST = expressed sequence tag.

[10] Rice is roughly divided into two types, japonica and indica. Japonica rice is usually grown in temperate climates, mostly in Japan. It is a short-grain variety characterized by its unique stickiness and texture and round grains that do not easily crack or break. Indica rice is usually grown in hot climates and is characterized by its long grain, and it tends to break easily. Most of the rice produced in southern Asia, including India, Thailand, Vietnam, and southern China, is indica rice.

[11] Within a plant, the "source" can be defined as a photosynthesizing tissue or organ with export of carbon skeletons, and the "sink" is one requiring import of carbon. "Sink strength" is the ability of a tissue or an organ to mobilize photo-assimilates, "sink capacity" (or "sink size") is the capacity of a tissue or organ to import and store further compounds from the source, and "sink activity" is the rate of respiration.

[12] Defined as the ratio of grain weight to total plant weight.

Table 3. Donors for various traits being used for developing the NPT.

Trait	Donors
Characteristic	
Short stature	MD2, Sheng-Nung 89-366
Low tillering	Merim, Gaok, Gendhjah Gempol, Gendjah Wangkal
Large panicles	Daringan, Djawa Serang, Ketan Gubat
Thick stems	Sengkeu, Sipapak, Sirah Bareh
Good grain quality	Jhum Paddy, WRC4, Azucena, Turpan 4
Resistance to	
Bacterial blight	Ketan Lumbu, Laos Gedjah, Tulak Bala
Blast	Moroberekan, Pring Ketan Aram, Mauni
Tungro	Gundil Kuning, Djawa Srut, Jimbrug, Lembang
Green leafhopper	Pulut Cenrana, Pulut Senteus, Tua Dikin

Source: Peng et al (1994).

germplasm is now referred to as tropical japonica. However, these first prototype lines had lower grain yield because of low biomass production and poor grain filling. In subsequent years, many improved NPT lines had normal grain filling and yield better than that of high-yielding indica varieties. Three NPT high-yielding lines, Dianchao 1, Dianchao 2, and Dianchao 3 (japonica type), were released in Yunnan Province of China during 2000-03, where they yielded more than 13 t/ha. Results of comparative studies between NPT and high-yielding indica indicated that NPT lines did not have sufficient biomass. Also, these high-yielding breeding lines (japonica type) and varieties were not accepted by the farmers in many countries because of poor grain quality. Thus, a new strategy was followed to introduce grain quality characteristics (medium-long slender grains) from indica germplasm. Crosses were made with indica varieties to improve grain quality. Intensive breeding and selection were carried out over the years. As a result, many breeding lines dubbed "improved-NPT" with indica rice grain giving 10–15% higher yield than IR72[13] were developed (Table 4). Recently, NSICRc158 and NSICRc222, both HYVs, and an improved NPT with superior grain quality were released in 2007 and 2009, respectively. Several other lines are in the pipeline for release.

Chinese scientists in 1997 proposed another plant type to develop super high-yielding rice inbreds and hybrids (Table 5). The most important morphological feature is that the uppermost three leaves should be long, erect, narrow, V-type, and thick. Long and erect leaves have larger leaf area and will not shade each other; therefore, light is used more efficiently; thick leaves have higher photosynthetic function and are not easily senescent. These morphological features mean a huge source of assimilates necessary for super HYVs.

A large sink and source are prerequisites for super high yield. However, many rice breeders have paid more attention to the sink than the source. Usually, we are interested in getting breeding materials with relatively high panicle number, large panicles, and desirable 1,000-grain weight, resulting in a very large sink but without enough source and therefore undesirable yield. Some of the proposed traits for increasing the yield potential of rice varieties are

a. Early vigor, moderate tillering capacity, and thin leaves at the vegetative stage.
b. Taller plants, lower panicle height, and thicker and stronger stems.
c. Erect, thick, dark green, and V-shaped leaves; high LAI;[14] and delayed leaf senescence in late stages.
d. Large and compact panicles, heavy grain weight, and long grain-filling duration. Some plant characteristics and growth conditions required to increase yield potential by 15% in the tropics are summarized in Table 6.

Table 4. Improved NPT with indica-type grain having 10–15% higher yield than IR72.

Designation	Grain yield (kg/ha)	Maturity (days)	BL	BB1	BB2	Tungro	GLH	BPH	Amylose
IR79195-42-1-3-1	6,667	123	R[a]	R	MS	S	MR	MR	I
IR79218-93-1-4-3	7,067	122	R	R	R	S	MR	MR	H
IR73718-23-2-1-3	6,782	121	MS	R	MS	S	MR	MR	I
IR79242-28-3-2-3	7,501	120	MS	R	MS	S	MR	MS	I
IR77700-84-2-2-2	7,540	118	MS	R	MS	S	MR	MR	H
IR79193-83-1-1-1	6,762	117	R	R	R	S	MR	MR	I
IR78119-24-1-2-2-2	7,237	114	MR	R	MS	R	MR	MR	I
IR75386-14-3-2-2	6,582	114	MR	R	MS	R	MR	MR	I
IR77734-93-2-3-2	6,635	111	R	R	MS	S	MR	MS	I
IR77512-128-2-1-2	7,003	110	S	R	MS	S	MR	MR	I

[a]R = resistant; MR = moderately resistant; S = susceptible; MS = moderately susceptible; I = intermediate; H = high. BL = blast; BB1 = bacterial blight race 1; BB2 = bacterial blight race 2; GLH = green leafhopper; BPH = brown planthopper.
Source: Virk (unpublished).

[13] IR72, a promising rice variety bred at IRRI, was released in the Philippines in 1988, yielding 5.9 t/ha during the dry season and 4.3 t/ha in the wet season.
[14] Leaf area index (LAI) is the one-sided green leaf area per unit ground area in broadleaf canopies, or the projected needleleaf area per unit ground area in needle canopies.

Table 5. Morphological traits of superior high-yielding rice.

Agronomic traits	Capacity
Plant height (cm)	100, with culm length of 70 cm
	No unproductive tillers
Leaf characteristics (uppermost three leaves)	Long: flag leaf, over the top of the panicle by 20 cm; the second leaf from the top is 10% longer than the flag leaf, and over the top of the panicle; the third leaf reaches the middle part of the panicle
	Erect: the leaf angles of the flag, second, and third leaves are 5, 10, and 20 degrees, respectively; staying erect till the maturing stage
	Narrow and V-type: the leaves look narrow but still have a width of 2 cm
	Thick: the dry weight of the uppermost three leaves is 0.98 g/100 cm^2, whereas that of 312S/Guiyunzhan, which yields 8.25 t/ha, is 0.73 g/100 cm^2
Plant type	Moderate erect type with moderate tillering capacity; nodding panicles after filled, with the panicle top about 60 cm from the ground; erect-leaf canopy without appearance of panicles
Panicle weight and number	Grain weight per panicle is 5 g; 2.7 million panicles per hectare
LAI and ratio of the leaf area to grains	LAI is about 6.5 based on the uppermost three leaves; the ratio of leaf area to grain weight is 100:2.3, meaning that, to produce 2.3 g of rice, 100 cm^2 of the upper three functional leaves are needed
Harvest index	0.55

Source: Yuan Longpin (1997).

Table 6. Some parameters required for increasing rice yield potential by 15% in the tropics.

Trait measured	Value
Mean daily radiation	18 MJ/m^2
Crop growth duration in main field	110 days
Mean light interception	70%
Radiation-use efficiency	1.5 g/MJ
Harvest index	0.50
Grain yield	18 × 110 × 0.7 × 1.5 × 0.5 = 1,039.5 g/m^2, 1,039.5/0.9/100 = 11.55 t/ha
Panicles per m^2	275
Spikelets per panicle	175
Grain-filling percentage	80%
1,000-grain weight	27 g
Grain yield	275 × 175 × 0.8 × 27 = 1,039.5 g/m^2, 1,039.5/0.9/100 = 11.55 t/ha

Source: S. Peng (Thursday seminar, personal communication).

Developing hybrids with higher yield potential. The phenomenon of heterosis or hybrid vigor[15] has been successfully exploited since the 1950s for increasing the productivity of cross-pollinated crops such as maize and sorghum. Major progress has been made to exploit hybrid vigor in self-pollinated crops such as rice. China has taken the lead in developing hybrid rice technology; about 50% of the rice area in China is under hybrid rice cultivation (Table 7). However, the global area under hybrid rice is only 3.4 million hectares. In general, hybrids have 10–15% higher yield than inbreds.

In general, hybrids show a 1-t/ha yield advantage over inbred cultivars (Fig. 9). With new advances in genetics and

Table 7. Area under hybrid rice in some countries, 2009.

Country	Total rice area (000 ha)	Area planted to hybrid rice (%)
Bangladesh	11,741	6.8
India	44,000	3.2
Indonesia	12,309	0.5
Philippines	4,460	4.3
Vietnam	7,414	9.4
U.S.	1,204	14.5
China	29,493	57.6

Source: IRRI (2010c).

[15] Heterosis, or hybrid vigor or outbreeding enhancement, is the increased function of any biological quality in a hybrid offspring. It is the occurrence of a genetically superior offspring from mixing the genes of its parents.

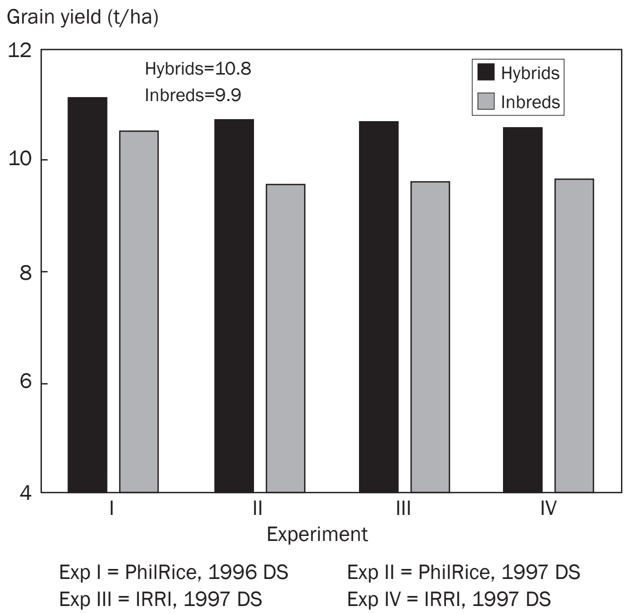

Fig. 9. A comparison between hybrids and inbreds in yield potential. Source: Peng (1999)

better understanding of heterosis, hybrid rice offers potential to further increase rice productivity. Among different male sterility systems, cytoplasmic male sterility (CMS) is the most stable system for hybrid seed production. Further efforts are being made to use the thermosensitive genetic male sterility (TGMS) system. However, it is markedly affected by the environment. Among the factors that affect hybrid rice dissemination, yield in hybrid seed production is the most critical. Recent research at IRRI and in other commercial programs showed that seed yield could be increased to 3–4 t/ha from the current 1–2 t/ha through breeding. Germplasm with high outcrossing[16] traits is being used in developing new female parents. Higher heterosis, which is required to achieve the advantage of hybrid rice over inbred varieties, is closely related to germplasm diversity. Heterotic patterns are being analyzed for developing hybrids with higher heterosis.

Good grain quality is one factor that influences acceptance by consumers. Therefore, high broken rice and chalkiness that can occur with hybrids need to be overcome. It is essential to improve the grain quality of high-yielding hybrid rice varieties for better acceptance by consumers. Resistance or tolerance should be introduced into hybrid rice parents to develop improved hybrids. Traditional breeding methods combined with new molecular technologies are being employed in hybrid rice breeding to speed up product development. The yield of hybrid seed has increased significantly, thus making it easier for farmers to purchase seed at a much lower cost. Molecular marker technology has helped in the determination of the purity of parental lines and hybrid seed and further accelerated efforts to transfer genes for fertility restoration and bacterial blight resistance into parental lines. Heterotic gene pools have been identified to obtain higher heterosis. QTLs/genes for hybrid vigor and heterotic gene blocks are being identified. Parental lines of hybrid rice with new yield potential are being developed using the approaches listed under Section 2, Shifting yield frontiers.

Introgression[17] *of yield-enhancing loci (wild species alleles)*. So far, in most plant breeding programs, intraspecific hybridization[18] involving diverse crosses between indica × indica and indica × japonica (tropical and temperate) has been used in rice improvement. Plant breeders are now tapping new genes to improve yield using wild species of *Oryza*. These wild species representing 10 genomic types, although inferior in phenotype, possess poor plant type and grain characteristics but they are an important source of new useful genes for rice improvement. Furthermore, with the new molecular markers available, it has become easy to track the introgression of wild species alleles into elite breeding lines. This has created new interest among breeders to exploit interspecific hybridization to identify and introgress QTLs from wild species for enhancing yield potential.

Transgressive segregation[19] for yield crosses of cultivated and wild species suggests that, despite inferior phenotypes, wild species contain genes that can improve quantitative traits such as yield. Tanksley and Nelson (1996) proposed advanced-backcross[20] (AB) QTL analysis to discover and transfer valuable QTL alleles from unadapted germplasm, such as wild species, into elite breeding lines.

QTLs from AA[21] genome wild species of rice for increased yield have been identified (Xiao et al 1996). A set of 300 BC_2 test-cross[22] families produced from the cross of *O. sativa* × *O. rufipogon* was analyzed. Wild species (*O. rufipogon*) alleles at two marker loci, RM5 (*yld1-1*) on chromosome 1 and RG 256 on chromosome 2 (*yld2-1*), were associated with enhanced yield. Both alleles (*yld1-1* and *yld2-1*) were associated with a significant increase in grains per plant. In another experiment, Xiao et al (1998) identified 68 QTLs. Of these, 35 (51%) had trait-improving alleles derived from phenotypically inferior wild species. Nineteen of these beneficial QTL alleles had

[16] Outcrossing in rice depends on the capacity of stigmas to receive alien pollen and the capacity of anthers to emit much pollen to pollinate other plants nearby.
[17] Introgression or introgressive hybridization is the movement of a gene (gene flow) from one species into the gene pool of another by repeatedly backcrossing an interspecific hybrid with one of its parent species.
[18] Intraspecific hybridization is hybridization between strains of a single species to develop high-yielding crops.
[19] Transgressive segregation is the formation of extreme phenotypes, or transgressive phenotypes, observed in segregated hybrid populations compared with phenotypes observed in the parental lines.
[20] Individuals in an unbalanced population do not have equal genetic contributions from each parent. Advanced backcross and inbred backcross (IBC) populations are examples of structured populations that are unbalanced.
[21] AA is a dominant true-breeding plant.
[22] An interspecific BC_2 test-cross population (V20A/*O. rufipogon*//V20B///V20B////Ce64) consisting of 300 families was evaluated for 12 agronomically important quantitative traits.

no deleterious effects on other characters. Since then, many laboratories have identified QTLs from wild species that could increase rice yield. However, more research is needed to verify the contribution of such wild species to enhanced yield in the genetic background of HYVs. Introgression of yield-enhancing loci from wild species could lead to increased yield potential of both inbred and hybrid rice varieties.

Pyramiding of genes[23]/QTLs for agronomic traits. So far, most genetic research has focused on identifying and pyramiding genes for resistance to insects and diseases. Only recently have near-isogenic lines[24] (NILs) for yield-related traits been generated (Kobayashi et al 2010). This has been further facilitated using molecular markers. NILs for different yield components have been produced in the background of IR64 (Kobayashi et al 2010).

Pyramiding of genes/QTLs for yield components would provide evidence if the individual yield-related QTLs, when combined, can increase yield without loss of yield due to compensation or interaction among agronomic traits. Pyramided QTLs resulting in higher yield over the recurrent parents would lead to breeding new varieties with higher yield potential.

Grain yield is largely determined by three yield components:

a. Number of panicles per unit area,
b. Number of spikelets (grain number) per panicle, and
c. Grain weight.

Genes for moderate tillering, namely, *FINECULM1 (FC1)* and *MONOCULM (MC1)*, and for high-tillering dwarf (*htd1*) could be used to regulate the number of tillers in order to maximize yield potential. The number of grains per panicle under the control of the *Gn1a* locus along with WFA/IFA1 (*OsSPL14)* will allow fine-tuning of panicle architecture favorable to the breeding of HYVs. Several genes, namely, *GS3, GW2, qSW5,* and *tgw6,* governing grain size have been reported to increase grain yield in rice. These genes could be used to improve grain size and thereby grain yield. To capitalize on these yield-related traits, it will be appropriate to incorporate QTLs/genes for grain filling (*G1F1*).

It is important in the future to pyramid newly isolated QTLs/genes governing agronomic traits in a single background to determine their effectiveness in enhancing yield. This could be achieved by developing NILs for each of the target genes through marker-assisted backcrossing. Such isogenic lines with well-defined genes could be used in pyramiding to ultimately analyze whether the compensation or interaction among traits could be overcome to break the yield ceiling in rice.

C_4 rice: modifying photosynthetic systems to raise yield. There are two main categories of plants based on the way they assimilate carbon dioxide into their systems. C_3 plants such as rice, during the first steps in CO_2 assimilation, form a pair of three-carbon atoms, whereas C_4 plants (maize) initially form four-carbon-atom molecules. To increase the yield potential of rice, one option is to increase the photosynthetic efficiency. The C_4 photosynthesis system is more efficient than that possessed by C_3 plants.

Converting C_3 plants to C_4 would be a long-term (15–20 years) option. C_4 rice could yield 50% more than the existing C_3 rice (Fig. 10). Also, it would have better nutrient- and

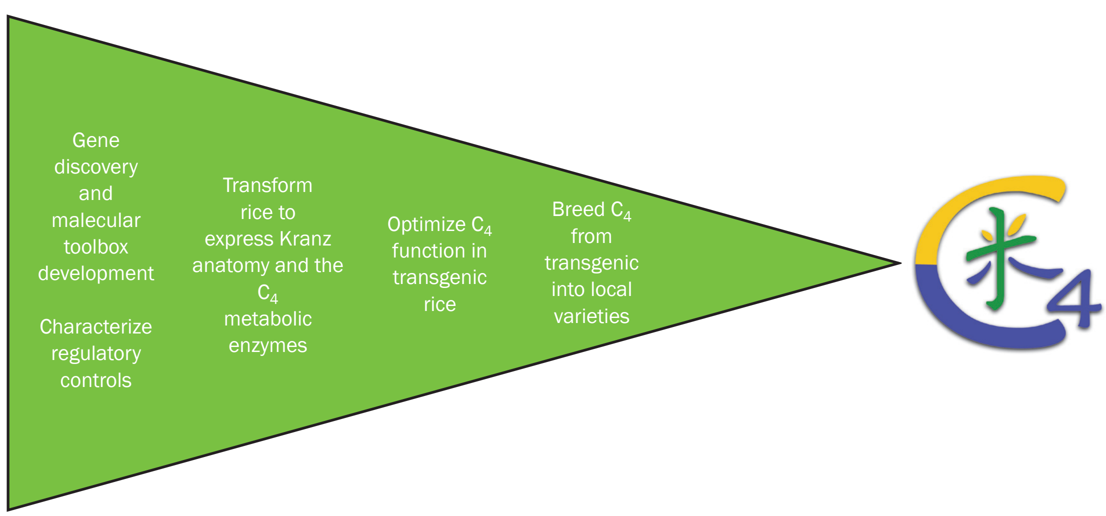

Fig. 10. The roadmap to C_4 rice. Source: IRRI (2010b).

[23] Gene pyramiding is a term that describes a genetic approach to achieving pest control and higher crop production. It is essentially a way of determining and introducing multiple genes that each impart resistance to an independent insect/microbial pest, or impart resistance to a single pest through independent host pathways.

[24] In genetically modified (GM) plants, isogenic initial lines mean those nongenetically modified plants from which the GM strains are derived. Thus, the only difference between GM plants and their derivative isogenic lines will be those genes that have been transferred transgenically.

water-use efficiency. C_4 photosynthesis requires less Rubisco and hence less nitrogen and less water. There are consistent and large differences in radiation-use efficiency (RUE) between C_3 and C_4 plants. Ultimately, RUE depends on the surplus of photosynthesis over respiration. Little can be done to decrease respiration, and so higher RUE, biomass, and yields require increased photosynthesis.

The pathways to success cannot be seen completely but the new tools of genomics will likely be useful for constructing C_4 crops such as rice.

Some advantages of C_4 photosynthetic systems over C_3 are:

a. Faster and more complete translocation of assimilates from leaves;
b. Reduced photorespiration;
c. Almost twice the efficiency in dry matter production per unit of water transpired;
d. Greater photosynthetic efficiency at high temperature; and
e. C_4 photosynthesis requires less Rubisco and hence less nitrogen and less water.

The most outstanding feature of high-capacity photosynthetic systems is the presence of two cell types, mesophyll cells and bundle sheath cells, which cooperate in carbon fixation. One of the major challenges to convert C_3 plants to C_4 plants is to understand

a. What mechanisms are used to coordinate the activities of the two cell types,
b. Which of the enzymes of C_4 photosynthesis are already expressed in the bundle sheath and how metabolism has been altered compared to the bundle sheath of C_3 plants, and
c. What processes in the C_3 bundle sheath might be disrupted by introducing C_4 photosynthesis.

Some of the strategies for converting C_3 to C_4 involve

a. Searching for genetic variability in the wild species germplasm/relatives of C_3 for C_4ness;
b. Incorporating such variability into C_3 plants through wide hybridization;
c. Identifying genes responsible for compartmentalization;
d. Identifying candidate genes for key components in C_4 plants;
e. Using comparative genomics for the identification of chromosomal regions carrying key traits/genes for C_4ness; and
f. Using genetic engineering approaches to transfer C_4 characteristics/key enzymes into C_3 plants.

The biggest challenge is to make the photosynthetic pathway of C_3 resemble that of C_4, by eliminating photorespiration. In C_4, photorespiration is rarely greater than 5% of the rate of photosynthesis, which in C_3 can exceed 30% of the rate of photosynthesis above 30 °C. In drought-prone ecosystems, yield could be maintained or increased with less water and less fertilizer, especially when coupled with the rising atmospheric concentration of CO_2. This is a long-term project of 15–20 years that would require extensive experimentation and exploratory research on several basic components before C_3 plants could be successfully converted to C_4 for commercialization. C_4 rice offers new potentials to raise rice yield (up to 50%) and enhance water- and nutrient-use efficiency.

Improving yield sustainability

Rice productivity and sustainability are continually threatened by a series of abiotic and biotic stresses, particularly in the era of global climate change. Among the abiotic stresses, drought, submergence, salinity, heat, and cold account for major losses in rice production. Similarly, biotic stresses, BB, blast, viral diseases (tungro), rice yellow mottle virus, grassy stunt, ragged stunt, BPH, whitebacked planthopper (WBPH), stem borer, and Asian and African gall midge are quite serious. These stresses account for more than 25% yield losses. In severe cases, losses can reach 80–100%. These losses are a major concern and they pose a risk for yield stability and sustainability. There is thus an urgent need to develop improved germplasm with multiple resistances to abiotic and biotic stresses. Besides conventional breeding, new molecular approaches, particularly marker-assisted selection and genetically modified (GM) plants, offer opportunities to meet these challenges to sustainable rice production.

Resistance to abiotic stresses. Rice production in unfavorable environments is mostly constrained by abiotic stresses. These areas are commonly overpopulated, and are characterized by widespread and persistent rural poverty. About 30% of the 700 million people in absolute poverty (with income of $1.25 per day) in Asia live in rainfed rice-growing areas in South Asia alone. The most serious abiotic stresses currently affecting rice production in Asia are drought, submergence, and salt stress, which annually affect about 23, 20, and 15 million ha, respectively. Low temperature adversely affects rice at high elevations and where rice is grown during the winter season in the subtropics, and heat stress is emerging as a serious threat to rice production as a consequence of climate change. The bulk of the rice produced in Africa is under rainfed conditions, accounting for more than 80% of the total rice cultivation. Stresses such as drought, salinity, submergence, low temperature, and iron toxicity are widespread in rice fields in Africa, contributing to persistent low rice yields. Iron toxicity and low soil fertility are common problems in Latin America, whereas low temperature is confined to southern Brazil, Uruguay, Argentina, and Chile. Considerable opportunities exist to at least double the yield in these areas through the use of stress-tolerant varieties.

Drought is the major constraint that affects rice production under both rainfed and upland conditions. In recent years, water scarcity even for irrigated rice has been the challenge. Conventional breeding has been practiced for the last several years and many drought-tolerant varieties have been released (Table 8). However, the tolerance of drought, particularly at the flowering stage, is very low. There is an urgent need to enhance tolerance of drought at various stages of plant growth. Recently, major progress has been made to identify a QTL (*qtl.12.1*) with larger effects on grain yield under water stress (Bernier et al 2007). Three more QTLs (*qtl3.1, qtl1.1, qtl 9.1*) for drought tolerance have been identified. These four QTLs are being pyramided with the hope that the drought tolerance of rice varieties will increase significantly. Phenotyping techniques are being improved to establish platforms for large-scale, precise measurements of yield and related traits under drought.

NILs possessing drought-tolerance QTLs are being analyzed physiologically to unveil the interaction between these QTLs and facilitate their effective use in breeding. A wide range of genetic resources, including African rice, *O. glaberrima*, are being used for the development of drought-tolerant varieties. Besides conventional breeding and pyramiding of QTLs, transgenic approaches, particularly using transcription factors such as dehydration-responsive element binding (DREB), and HARDY,[25] offer new potential to further increase the tolerance of drought beyond what has been achieved already. At IRRI, transgenic lines of IR64 are under field evaluation to determine their performance under drought stress.

Rice is sensitive to flooding during germination, which hinders direct seeding in rainfed areas, and also during the vegetative stage when completely submerged. Stagnant partial flooding of 0–50 cm for most of the season also affects considerable areas, estimated at more than 5 million ha in India and Bangladesh alone. More progress has been made to identify a submergence-tolerance (*SUB1*) gene (Septiningsih et al 2009). The *SUB1* gene has been transferred through MAS into six mega-varieties[26] and three new varieties (IR64-Sub1, Swarna-Sub1, and BR11-Sub1) have been released in four countries (Table 9). The *SUB1* gene confers an advantage of 1–3 tons of grain yield following flooding for 10–15 days. The discovery of

Table 8. Drought-tolerant varieties of rice released during 2009-10.

Variety name	Year released	Country where released	Special features
IR74371-54-1-1 Sahod Ulan	2009	Philippines	Early, drought tolerant, suitable for both direct-seeded and transplanted situations
IR74371-54-1-1 Sukha dhan 2	2010	Nepal	Medium slender grain, drought tolerant
IR80411-49-1-1-B Tarharra1	2009	Nepal	Early, drought tolerant, suitable for both direct-seeded and transplanted situations
IR74371-70-1-1 Sahbhagi dhan	2010	India	Early, drought tolerant, suitable for both direct-seeded and transplanted situations
IR74371-70-1-1 Sukha dhan 3	2010	Nepal	
IR74371-70-1-1 (prereleased line)	2011	Bangladesh	
IR74371-46-1-1 Sukha dhan 1	2010	Nepal	Early, drought tolerant, suitable for both direct-seeded and transplanted situations

Source: Kumar (personal communication).

Table 9. Rice varieties tolerant of submergence developed through MAS.

Variety name	Year released	Countries where released	Special features	Prerelease lines in the pipeline
IR64-Sub1 (Submarino 1)	2009	Philippines	Tolerant of flash flood (up to 2 weeks of complete submergence)	Samba Mahsuri-Sub1, CR1009-Sub1, TDK-Sub1, Ciherang-Sub1, PSB Rc18-Sub1
Swarna-Sub1	2009	India	Yielded 1–2 t/ha more than the original parents under stress, but no significant yield difference under normal conditions	
Swarna-Sub1 INPARA-4	2009	Indonesia		
Swarna-Sub1				
BRRI dhan51	2010	Bangladesh		
BR11-Sub1 INPARA-5	2010	Indonesia		

Source: Septiningsih (personal communication).

[25] DREB and HARDY are transgenic genes for drought tolerance.

[26] The mega-varieties Samba Mahsuri, Swarna, and CR1009 from India, IR64 from the Philippines (IRRI), Thadokkham 1 (TDK1) from Laos, and BR11 from Bangladesh were used as recipient parents. They were called mega-varieties because they were popular and were planted, for many years, on a minimum of 1 million hectares.

the *SUB1* gene conferring tolerance of submergence has made it feasible to use gene-based MAS for developing submergence-tolerant varieties. *SUB1* is now introduced into a wide range of genetic backgrounds to develop more tolerant varieties that are also adapted to longer-term stagnant flooding. Lines tolerant of anaerobic germination will be developed from the best sources identified and through the use of MAS.

The tolerance traits of all submergence types will be characterized at the physiological level and the best donors for breeding will be identified and used in crosses to enhance submergence for longer duration (more than 15 days). The *SUB1* gene that confers submergence tolerance is now being transferred into Africa mega-varieties, using IRRI donors. The improved mega-varieties (in terms of submergence tolerance) will be evaluated on a scale in multilocation trials at "hot spots" in Africa. Further attempts are being made through gene discovery approaches to identify alleles/genes other than *SUB1* conferring submergence. Pyramiding of *SUB1* with the newly identified genes will enhance tolerance of submergence over a longer period (3–5 weeks of submergence).

Poor soils with excess salt and deficiency in certain plant nutrients limit rice productivity in most rainfed rice areas, and several million ha of land suited to rice production in Asia and Africa are currently unexploited because of salinity and other related soil problems. Rice is suitable for reclaiming these soils because it thrives well under flooding, and has high potential for genetic manipulation. Rice productivity in salt-affected areas is very low, 1.5 t/ha, but this can reasonably be raised by at least 2 t/ha. Germplasm with different mechanisms of tolerance of salinity has been identified. A few genes/QTLs with different modes of tolerance have been identified. Some of these QTLs have been tagged. *Saltol* and other QTLs for seedling-stage tolerance and one for the reproductive stage will be tagged to develop varieties tolerant at both stages and the physiology and genetics of tolerance at both stages will be advanced. Some of the recently released salt-tolerant varieties are listed in Table 10. MAS has been practiced to transfer the *Saltol* gene into a mega-variety of Bangladesh (BR11).

High temperature will become an increasing problem because of climate change. In the Sahel region of Africa, temperatures above 40 °C are experienced quite often during rice cultivation periods. Heat stress causes high sterility, leaf yellowing, and accelerated development, leading to low yield potential in sensitive rice varieties. Rice plants are most sensitive at the flowering and ripening stages. Both yield and grain quality are adversely affected. Donors for tolerance of high temperature have been identified by screening improved and traditional rice varieties. *O. glaberrima* could be a useful genetic resource since it has a habit of early-morning flowering and high transpiration with sufficient water, both of which are convenient traits for avoiding heat stress. These donors have been used in a crossing program to incorporate tolerance of high temperature into elite cultivars suitable for different growing environments. Available introgression lines from crosses of wild species (*O. officinalis* and *O. minuta*) are being screened for early day flowering (EDF). QTL mapping is in progress to facilitate the use of MAS in developing improved heat-tolerant cultivars. Advanced breeding lines involving crosses between elite rice lines and heat-tolerant donors (N22, IR6) have been developed and are being evaluated in hot spots in different countries to identify promising heat-tolerant lines.

Resistance to biotic stresses. Rice is attacked by more than 100 diseases and insects. However, some of these, such as BB, blast, tungro virus, sheath blight, and rice yellow mottle virus (RYMV), are predominant diseases in Asian and African countries. Similarly, planthoppers such as BPH, whitebacked planthopper (WBPH), stem borers, and both Asian and African gall midge cause huge damage to the rice crop. These hoppers are vectors of several viral diseases such as grassy stunt, ragged stunt, rice dwarf streak virus, and tungro.

With new cultivation systems involving intensive cultivation with high input, including monoculture of rice over larger areas with planting throughout the year and frequent changes in the pathogen populations and new biotypes and changed structure of pest populations, and the emergence of new diseases such as false smut, it is essential to develop varieties with multiple resistance to pests.

Over the years, a large number of genetic donors have been identified and numerous varieties resistant to diseases have been

Table 10. Recently released salt-tolerant varieties of rice.

Variety name	Year released	Countries where released	Special features	Prerelease lines in the pipeline
IR52713-2B-8-2B (CSR23)	2005	India	Tolerant of sodic soil	IR72046-B-R-3 for West Bengal, India
IR63307-4B-4-3 (BRRI dhan47)	2008	Bangladesh	Salt tolerant for boro season	IR72579-B-3-2-3-3 for Bangladesh
IR63307-4-B-4 (NSICRc 182 or Salinas 1)	2009	Philippines		
R66946-3R-149-1- (BINA Dhan 8)	2010	Bangladesh	Salt tolerant for boro and T. aman season	IR73678-6-9-B (AS 996) for Bangladesh boro season
IR71896-3R-8-3-1				Philippines
IR68144-2B-2-2-3-2 (NSICRc 172)	2008	Philippines	High-iron rice, tolerant of zinc-deficient soils	

Source: Gregorio (personal communication).

released. Genetics of resistance have been studied and more than 30 genes (*Xa1–Xa35*) for BB resistance and 40 genes (*Pi1–Pi40*) for blast resistance have been identified. These genes have been transferred into elite breeding lines and several varieties have been released by the national agricultural research and extension systems (NARES) for commercial cultivation. Similarly, many varieties resistant to tungro have been released. A number of varieties with multiple resistance have been released (Table 11). Cultivation of these varieties has reduced the use of chemicals and saved millions of dollars.

During the last two decades, a large number of genes for resistance to disease have been tagged with molecular markers. Some of these genes for resistance to BB and blast have been transferred through MAS in both indica and japonica cultivars. Recently, MAS has been employed to pyramid genes for resistance to BB. These pyramided lines with two or more gene combinations (*Xa4, xa5, xa13, Xa21*) have shown higher resistance than with single-gene transfer. As many as six varieties and eight hybrids have been released through MAS (Table 12). With advances in molecular technology involving a new generation of markers such as single nucleotide polymorphisms (SNP), this would further accelerate the breeding of rice varieties with multiple resistance to different pathogens. Major advances have been made to produce transgenic rice, com-

Table 11. IR rice varieties with multiple resistance to diseases and insects.

IR variety	Reaction[a]									
	Blast	Bacterial blight	Grassy stunt	Tungro	GLH[b]	BPH[c] biotype			Stem borer	Gall midge
						1	2	3		
IR5	MR	S	S	S	R	S	S	S	MS	S
IR8	MR	S	S	S	R	S	S	S	S	S
IR20	MR	R	S	MR	R	S	S	S	MR	S
IR22	S	R	S	S	S	S	S	S	S	S
IR24	S	S	S	S	R	S		S	S	S
IR26	MR	R	MR	MR	R	R	S	R	MR	S
IR28	R	R	R	R	R	R	S	R	MR	S
IR29	R	R	R	R	R	R	S	R	MR	S
IR30	MS	R	R	MR	R	R	S	R	MR	S
IR32	MR	R	R	MR	R	R	R	S	MR	R
IR34	R	R	R	R	R	R	S	R	MR	S
IR36	R	R	R	R	R	R	R	S	MR	R
IR38	R	R	R	R	R	R	R	S	MR	R
IR40	R	R	R	R	R	R	R	S	MR	R
IR42	R	R	R	R	R	R	R	-S	MR	R
IR43	R	R	S	S	R	S	S	S	MR	S
IR44	R	R	S	R	R	R	R	S	MR	S
IR45	R	R	S	S	R	S	S	S	MR	S
IR46	R	R	S	MR	MR	R	S	R	MR	S
IR48	R	R	R	R	R	R	R	S	MR	–
IR50	MS	R	R	R	R	R	R	S	MR	–
IR52	MR	R	R	R	R	R	R	S	MR	–
IR54	MR	R	R	R	R	R	R	S	MR	–
IR56	R	S	R	R	R	R	R	R	MR	–
IR58	R	R	R	R	R	R	R	S	MR	–
IR60	R	R	R	R	R	R	R	R	MR	–
IR62	MR	R	R	R	R	R	R	R	MS	–
IR64	MR	R	R	R	R	R	MR	R	MR	–
IR65	R	R	R	R	R	R	R	S	MS	–
IR66	MR	R	R	R	R	R	R	R	MR	–
IR68	MR	R	R	R	R	R	R	R	MR	–
IR70	R	S	R	R	R	R	R	R	MS	–
IR72	MR	R	R	R	R	R	R	R	MR	–
IR74	R	S	R	R	R	R	R	R	MR	–

[a]S = susceptible, MS = moderately susceptible, MR = moderately resistant, R = resistant. Reactions were based on tests conducted in the Philippines for all diseases and insects except for gall midge, conducted in India. [b]GLH = green leafhopper. [c]BPH = brown planthopper.
Source: Khush and Virk (2005).

Table 12. Rice varieties resistant to bacterial blight developed through MAS.

Variety	Genes for BB resistance	Country
NSICRc142	Xa21 + Xa4	Philippines
NSICRc154	Xa21 + Xa4	Philippines
Improved Pusa Basmati	Xa21 + xa5 + xa13	India
Improved Samba Mahsuri	Xa21 + xa5 + xa13	India
Xieyou 218, Zhong you218, Ilyou 218, Zhongbai you 1	Xa21	China
Guodao 1, Guodao 3, Neizyou, Ilyou 8006	Xa4 + xa5 + xa13 + Xa21	China
Angke	Xa4 + xa5	Indonesia
Conde	Xa4 + Xa7	Indonesia

Source: Compilation from different sources.

monly referred to as GM plants with new genetic properties. A number of laboratories have produced transgenic rice lines with herbicide resistance, resistance to both abiotic and biotic stresses, improved nutritional quality, etc. Earlier, indica rice was difficult to transform; however, the availability of *Agrobacterium* strains and its co-cultivation with transgenes using immature embryos has resulted in a high frequency of production of transgenics in indica rice lines. High-throughput systems have become available to transform both indica and japonica rice.

Transgenic rice with the *Xa21* gene has shown increased resistance to BB under both screenhouse and contained field tests at PhilRice and IRRI. Transgenic technology offers potential to develop germplasm/varieties resistant to diseases such as sheath blight, whereas conventional breeding has met with limited success.

Rice is attacked by a large number of insects, of which planthoppers (BPH, WBPH, GLH), stem borers (yellow and pink), and gall midge (Asian and African) are the most destructive in many parts of Asia and Africa. Like diseases, insects can cause heavy losses in rice yield. As an example, hopperburn resulting from BPH attack could lead to as high as an 80–100% yield loss.

The genetics of resistance to various insects has been studied, donors identified, and genes transferred to develop a large number of insect-resistant varieties. As many as 25 genes (*Bph1–Bph25*) for resistance to BPH, 13 genes (*Wbph1–wbph13*) for WBPH, and 10 genes (*Glh1–Glh10*) for GLH, including several QTLs, have been identified. Many of these genes/QTLs have been tagged with molecular markers.

IRRI has begun developing isogenic lines using a set of BPH resistance genes. These isogenic lines will be used in gene pyramiding to develop BPH-resistant varieties. Pyramiding of new genes/QTLs for resistance to hoppers looks like a promising technology for the future to overcome the serious threat posed by hopper attack on rice in Asia. Table 11 indicates IRRI rice varieties with multiple resistance to diseases and insects.

One of the major advances in enhancing resistance to insects is the production of transgenic *Bt* rice. Conventional breeding approaches to develop stem borer resistance have not met with much success in rice. A number of *Bt* genes (*Cry1, Cry1a, Cry2A*) conferring resistance to stem borer have been transferred through transgenic approaches in many laboratories. Furthermore, these transgenes (*Bt* genes) have been pyramided to develop a wide spectrum of resistance to stem borer (Zhang 2009). Transgenic technology has great potential to develop germplasm resistant to insects, particularly when conventional breeding approaches have not been successful. Although transgenic rice was produced as early as 1988, no transgenic rice has yet been released for commercial cultivation.

Engineering rice with biological nitrogen fixation. Rice accounts for nearly 20% of global N-fertilizer consumption, but, on average, only 30–40% of the N applied is absorbed by the rice plant. The rest is lost and it is these "reactive" forms of nitrogen that have many undesirable impacts on the environment. Building on earlier research and recent advances in science, we will explore engineering new rice varieties with capability for biological nitrogen fixation (BNF), which is a very energy-intensive process. Therefore, having this BNF trait, possibly even in a future C_4 rice, would allow saving N fertilizer without sacrificing yield. Advanced research institutions with active research interest in nitrogen fixation will be involved in exploring several strategies to enable rice to fix its own N. Improving the endophytic associations between rice and nitrogen-fixing bacteria is attempted as a priority for developing rice capable of nitrogen fixation. In preliminary studies, some wild species germplasm has shown endophytes to support BNF.

Healthier rice varieties. Among the major micronutrient problems common in rice-consuming countries, iron, zinc, and vitamin A deficiencies are the most common. It is estimated that more than 3 billion people in the developing world are iron-deficient. Almost 3 million children of preschool age have visible eye damage owing to vitamin A deficiency. Estimates of the subclinical prevalence of vitamin A deficiency range from 100 to 250 million people. Billions of people are at risk for zinc deficiency. The cost of these deficiencies in terms of lives and quality of life lost is enormous. Current rice varieties do not provide enough micronutrients for leading healthy productive lives. Since rice is the dominant cereal crop in most Asian countries and is the staple food for more than half of the world's population, even a small increase in micronutrient content in rice grains would have a significant impact on human health. Moreover, biofortification of breeding staples with high micronutrient content has evolved as a new strategy to overcome micronutrient malnutrition. Biofortification is likely to reach rural households as the improvements are targeted to the crops and foods that can be grown and sourced locally and they are expected to have a sustainable impact. IRRI intends to develop nutritious rice by combining/pyramiding three quality traits (pro-vitamin A + high iron + high zinc). Molecular markers offer great potential to pyramid these traits and develop nutritious rice.

Screening of rice germplasm has not shown any accession with pro-vitamin A in the rice grain. Hence, to develop pro-vitamin A-enriched rice, a genetic engineering approach was undertaken. Ye et al (2000) used a transgenic approach and developed rice with pro-vitamin A properties. Since then, several attempts have been made to enhance pro-vitamin A. GR1 events in variety Cocodrie with a single locus and single intact insert (no selectable marker) showed carotenoid up to 8 µg/g. Later, Paine et al (2005) produced transgenic rice termed a GR2 event in variety Kaybonnet with as high as 25 µg/g carotenoid. The carotenoid locus from the leading GR2 event has been introgressed at IRRI into three mega-varieties of rice (IR64, PSBRc18, and BR29) using marker-aided backcrossing. Evaluations of transgenic introgression lines in screenhouse and confined field tests have shown that these mega-varieties are similar in performance in agronomic characteristics to the recurrent parents but have higher carotenoid. Investigations on bioavailability and suitability for human consumption are in progress. It is expected that, by 2013, golden rice will become available for commercial release. However, regulatory and biosafety requirements need to be met before that occurs.

HYVs possessing enhanced grain zinc content are being developed. A number of donor parents have been identified. Some of the japonicas have shown higher zinc in the polished grain. Advanced breeding lines have been developed from crosses of elite indica varieties with high-zinc japonicas. These lines are under evaluation in target countries such as Bangladesh and India to develop varieties with high zinc content. Breeding lines with as high as 23 µg/g zinc in the polished grains have become available to meet the target of high-zinc rice. A number of mapping populations such as recombinant inbred lines (RILs) and doubled-haploid (DH) lines have been generated. These populations are being genotyped using both simple sequence repeat (SSR) and SNP markers to identify QTLs for high zinc content. The newly indentified QTLs will be used through MAS to transfer high zinc content into commercial rice cultivars. G × E interactions involving high-zinc breeding lines are being investigated using multilocation testing. In addition, a bioavailability study on higher zinc rice is in progress. These results will be used in consumer acceptance/promotion studies.

Initial studies have shown limited genetic variability for iron content in rice germplasm. One IRRI breeding line, IR68144-2B-2-2-3-2, was released as a high-iron rice variety (NSICRc172). However, polished rice has only 2.5 µg/g iron. Thus, genetic engineering approaches are being used to achieve the target of 14 µg/g iron in the polished grain. Transgenic rice has been produced with as high as 8 µg/g iron. To further enhance iron content, new gene constructs, including iron transporter genes and an appropriate promoter, are being used to raise the iron content in polished rice grain.

Improved management strategies

Nutrients. Several factors affect yield increase and profitability in rice, and nutrient management is one, but nutrients can damage the environment too if they are insufficient or overfeeding is done. Rice needs essential nutrients such as nitrogen, phosphorus, and potassium, which are typically not found in the soil in sufficient amounts. The farmers' practice in fertilizer application with regard to timing and method of application could significantly reduce nutrient losses and improve nutrient uptake. Since 2000, the successful development of site-specific nutrient management (SSNM) in different irrigated rice-growing environments of Asia has shown a possible yield increase and more nutrient-use efficiency. Studies revealed that SSNM improved farmers' rice yield by 0.5 t/ha in the Mekong Delta of southern Vietnam (Hach and Tan 2007) and by 0.2 t/ha in Ha Nam and by 0.34 t/ha in Ha Tay in the Red River Delta of northern Vietnam (Nga et al 2010). Rice yields are dependent on the specific area and season with regard to climate, variety, and crop management practices, such as for the nutrient needs of the rice plant. SSNM enables rice farmers to optimally supply their crop with essential nutrients. This would help farmers supply rice with essential nutrients whenever needed to ensure the best "feeding" of the rice crop to meet its nutrient requirement. This enables rice farmers to tailor nutrient management to the specific conditions of their field, and it provides a framework for nutrient best management practices for rice (IRRC 2010).

SSNM not only establishes a yield increase but also reduces labor costs with proper management practices. The principles of SSNM can accommodate a wide range of socioeconomic conditions, including a labor shortage. Small amounts of additional labor may be required, but labor costs for nutrient management are relatively small compared with those for land preparation, transplanting, or harvesting (Witt et al 2002). Also, modified SSNM raised rice yields slightly, using significantly less fertilizer and no increase in labor (IRRC 2007).

Direct-seeded rice. Initially, direct seeding was the oldest way of planting rice wherein seeds were broadcast in prepared land. But, farmers experienced more weeds, resulting in more cost for labor, uneven plant stand, and a crop that was sometimes lost when rain occurred. Nowadays, the most common method of crop establishment for rice in Asia is transplanting, wherein young rice seedlings are inserted into a well-puddled and leveled wet field either manually or by machine. This practice requires less irrigation, less weeding, and fewer seeds, yet at the same time provides higher yields. But, a well-performed transplanting operation requires a lot of labor for different activities such as seed selection, soaking of seeds prior to their initial sowing, careful management of nursery beds, and proper control of water in the nursery and in the field. And, studies showed that puddling for transplanted rice has toxic effects on the soil environment for the succeeding wheat and other upland crops (Kumar 2009). Puddling requires lots of scarce water at a time when there is little water in the reservoirs. It also destroys soil structure and adversely affects soil productivity. Direct-seeded rice (DSR) is introduced to replace transplanted rice to reduce labor charges. DSR removes puddling and drudgery of transplanting young rice seedlings, and it provides an option to solve the problem of soil toxicity. DSR does not need continuous submergence so it reduces the overall water requirement of the rice crop because water is given only to keep soil continuously moist. DSR overcomes the problem of seasonality in the labor requirement for rice nursery raising and transplanting operations. In India, nondevelopment of groundwater in kharif, the late onset of monsoon, and drudgery of operations often delay rice transplanting, which leads to late vacating of fields, forcing farmers to plant wheat after the optimum sowing time. DSR facilitates the timely establishment of rice and succeeding winter crops. Unlike puddled fields, DSR fields do not crack and this helps save irrigation water. Surface-retained residue serves as a physical barrier to the emergence of weeds, moderates the soil temperature in summers and winters, conserves soil moisture, and adds organic matter and nutrients to the soil upon decomposition. From farmers' point of view, DSR saves time and, if the crop is established earlier, can lead to increased production and less cost of fuel and labor requirement, thus leading to higher net returns.

Mitchell et al (2004) revealed that farmers in the rainfed lowlands tend to use DS methods when TP cannot be conducted due to labor or water constraints. Results showed that the frequency distribution of grain yield for DS and TP (transplanted) rice was not significantly different from one another (Fig. 11). The mean grain yield response was 6% higher in TP rice than in DSR but the highest yielding trial was found in a DS environment due to a very high plant density.

Pest management. One of the challenges to increasing rice yield is developing sustainable management techniques since rice pests have the potential to reduce crop yields, which means managing crop pests in a way in which future crop production is not threatened (Jahn et al 2001). Rice pests include weeds, pathogens, insects, rodents, and birds. Pests are a serious constraint to rice production, and yield loss estimates differ from one source to another. Global crop losses in rice come from weeds, animal pests, and diseases at 10.2%, 15.1%, and 12.2% of the attainable yield, respectively (Norton et al 2010). Studies show that several factors can contribute to pest outbreaks, such as overuse of pesticides, high rates of nitrogen fertilizer application, and weather conditions. Integrated pest management (IPM) attempts to use different methods of pest control (cultural practices, biological and mechanical) to keep pest populations below the number that would cause economic loss, and recommends pesticides as a last resort (Acquaah 2002). Insecticide use in the 1960s not only killed insect pests, but their natural predators as well. And, worst of all in the later years, with the continued and increased dosages of chemicals and their toxic mixtures, this also destroyed the ecological balance. Matteson (2000) reported that insecticide wipes out predators along with their food supply, leaving fields open for pest buildup.

IPM extension education in depth and quality is required to discourage unnecessary insecticide use that upsets this natural balance, and to empower farmers as expert managers of a healthy paddy ecosystem. Farmers' skill and collaboration will be particularly important for the sustainable exploitation of the potential of new, higher-yielding and pest-resistant rice varieties. IPM in extension systems failed, although mass media campaigns encouraging farmer participatory research can reduce insecticide use (Matteson 2000). The success of IPM mainly depends on farmers' understanding of a healthy crop that is resistant to pests and the help of natural/biological control. Nowadays, insecticide use is considered destructive under most circumstances because it destroys the natural balance since abundant natural enemies in tropical Asian irrigated rice usually prevent significant insect pest problems.

The buildup of resistance to chemicals over time can lead

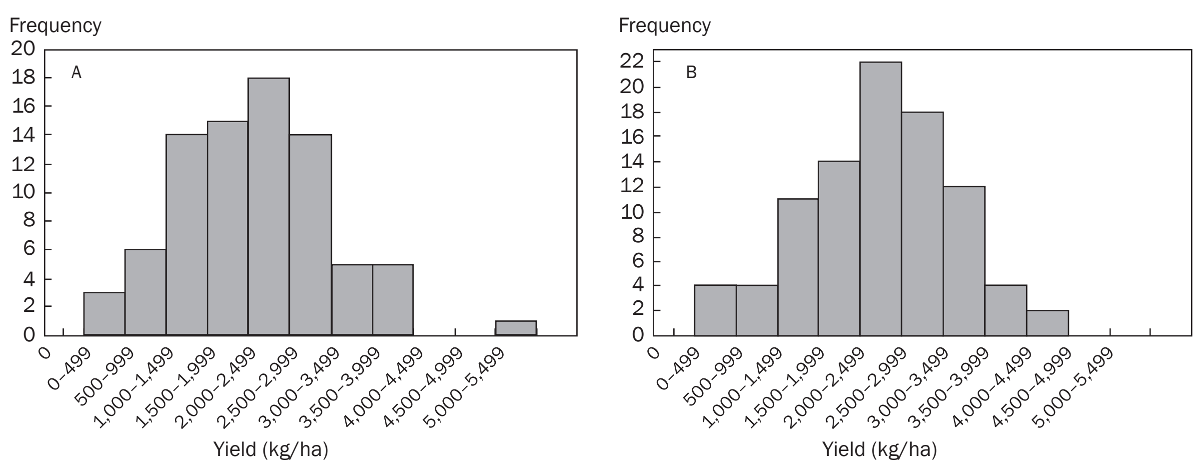

Fig. 11. Frequency distribution of grain yield of (A) 81 direct-seeded environments and (B) 91 transplanted environments for experiments conducted in Thailand, Laos, and Cambodia. Source: Mitchell et al (2004).

farmers to apply more and larger amounts to manage pest outbreaks (Norton et al 2010). This not only affects human health but also increases production costs. Developing rice varieties resistant to a wide range of pests has been the preference in rice breeding and the most ecological and desirable method employed in pest control. Not only does this contribute to a healthier environment and minimal risk to farmers, breeding HYVs with multiple resistance also increases the profitability of rice production (Heinrichs 2007). Varietal resistance is essentially free to farmers and it increases the susceptibility of insect pests to insecticides. Even in the early years, studies showed that rice varieties with multiple resistance to insects and diseases were already grown on more than 20 million hectares in Asia and Central and South America. Progress in the breeding and distribution of resistant rice varieties has been phenomenal (Heinrichs et al 1985). With IPM and varietal resistance to insect pests and diseases, yield can be stable and profitable.

Grain quality

Rice is generally consumed as a polished grain. Nutritional components such as minerals and vitamins are either absent or present at low levels in polished grains (Lucca et al 2006). Rice provides a staple source of energy, protein, and other nutrients to half of the world population. More than 90% of rice seeds consist of starch and protein by dry weight. The quantity and property of starch and protein thus play a dominant role in the yield and quality of rice. The amylose content of starch is a determining factor in eating and cooking quality, while the amount of storage proteins affects the nutritional quality of rice (Duan and Sun 2005). Rice quality is a combination of physical and chemical characteristics that are required for a specific use by a specific user. Genetic characteristics to consider are shape, size, color, chalkiness, bulk density, thermal conductivity, equilibrium moisture content, and flow ability. But, breeding a high-yielding rice variety with the best marketability for grain quality is not that easy. And, before the rice is consumed, it needs to be polished after threshing. When the temperature increases during polishing, the amount of chalk in rice grains also increases, resulting in lower milling yield. Farmers are paid less for broken kernels and chalky grains. Other qualities of rice grain depend on farmers' preferences, which are cooking quality, whiteness, and aroma.

Breeding for grain quality of rice aims to meet the demands of local consumers as well as foreign markets to command a high price and achieve high yield and profitability for producers. High-quality rice can offer producing countries additional opportunities for generating higher export revenues (Fitzgerald et al 2008). One most important grain quality of rice is chalkiness since it affects milling quality and consumer acceptance of rice. Chalkiness in grain occurs most commonly when high temperatures are experienced during grain development. This characteristic affects the acceptability of hybrid rice (IRRI 2010a).

Malnutrition

Of all the staple food crops, rice accounts for the dietary energy requirements of almost half the world population. More than 90% of the world's rice is produced and consumed in Asia. It is the second most important crop in the world (after wheat, which has an annual cultivation area of 213 million hectares) and is grown annually on 151.54 million ha, with an annual production of 593 million tons and an average productivity of 3.91 t/ha (Rai 2002).

GR (Golden Rice) is a new rice variety that has been genetically modified to contain beta-carotene, a source of vitamin A. This modification was undertaken as a strategy to overcome vitamin A deficiency, which is widespread in the less developed countries of Asia. Vitamin A deficiency (VAD) is an important nutritional problem in the developing world. Vitamin A's primary physiological role is in vision and maintenance of the general health of the eye, with a myriad of secondary roles, such as maintenance of the immune system. Supplementation or increased consumption of carotenoids in deficient populations has been found to substantially reduce morbidity and mortality for children. VAD is prevalent among the poor in Asia, because their diets are dependent on rice, which does not contain vitamin A precursors (Robertson et al 2005). GR was developed to accomplish fortification through genetic modification.

Robertson et al (2005) showed the importance of Golden Rice in comparison with other interventions that depend on existing dietary patterns. Their results showed that both fortification and GR would help to improve the health status of the poor, and GR may have a role to play as a complement to other food-based interventions. In addition, wheat consumption is also rising throughout Asia, and this will make fortification more effective. However, the very poorest households will be much slower in following these consumption trends, and GR may have an important role for low-income consumers.

The importance of targeting foods eaten by the poor can be seen in household consumption survey data from Indonesia and Bangladesh (Table 13). Although these are less precise than the individual food intake data from Cebu, they provide a useful comparison. GR would deliver two to three times as much vitamin A to the poor in Indonesia and Bangladesh compared with GR and yellow maize in Cebu. The poorest consumers in Indonesia would obtain three times as many RAEs from GR as from wheat fortification, and, in Bangladesh, RAEs from GR would provide half as many as those from wheat. This is in contrast to Cebu, where wheat fortification provides five times as many RAEs as GR. Although well-implemented fortification of wheat flour and cooking oil would each provide the poor with higher absolute levels of vitamin A in Cebu, this would not be the case for the poor in other Asian countries. Thus, GR is better targeted toward the poor than wheat fortification. The delivery of vitamin A depends on the relative consumption of rice and wheat within Asia. Thus, the relative potential of fortified wheat flour and Golden Rice for improving vitamin A status will also vary substantially from country to country.

Table 13. Potential additions to vitamin A intake from Golden Rice and wheat fortification in Indonesia and Bangladesh compared with Cebu, Philippines.

Country	Income group				
	Bottom	Near bottom	Middle	Near top	Top
Indonesia					
Rice consumption per capita (kg daily)	0.255	0.297	0.319	0.325	0.306
Wheat consumption per capita (kg daily)	0.006	0.010	0.015	0.023	0.034
Golden Rice (daily RAEs)	42	49	53	54	51
Fortified wheat (daily RAEs)	17	29	45	68	103
Ratio of wheat RAE to GR RAE	0.4	0.6	0.9	1.3	2.0
Bangladesh					
Rice consumption per capita (kg daily)	0.393	0.456	0.485	0.508	0.498
Wheat consumption per capita (kg daily).	0.035	0.033	0.035	0.026	0.040
Golden Rice (daily RAEs)	65	76	81	85	83
Fortified wheat (daily RAEs)	105	99	106	79	120
Ratio of wheat RAE to GR RAE	1.6	1.3	1.3	0.9	1.4
Cebu, Philippines					
Golden Rice + yellow maize RAEs	26	28	29	32	33
Fortified wheat RAEs	132	150	153	159	203
Ratio of wheat RAE to GR RAE	5.0	5.4	5.3	4.9	6.2

Source: Robertson (2005). Raw data on consumption of rice and wheat: Bangladesh Bureau of Statistics (1998), Indonesia Central Bureau of Statistics (2000); for Cebu, National Nutrition Council (2001).
Note: In the National Nutrition Survey of 1998, Cebu had higher than the national average incidence of severe deficiency and low (but not deficient) vitamin A blood serum levels were found among 52% of the children under 5.

Preparing for climate change

Rice production is likely to be affected by climate change but, at the same time, rice production affects the environment. Climate change is projected to affect rice production through changes in the concentration of carbon dioxide, and a rise in average temperature. In addition, it is expected that climate change will increase the frequency of extreme climatic events (i.e., storms, drought, monsoon, heavy rainfall), thus increasing the probability of flooding. In delta regions, it is expected that climate change will raise sea levels and the risk of flooding as well as salinity problems in rice-growing areas (Wassman et al 2004).

Increases in temperature above the current mean temperature for *ceteris paribus* conditions are expected to reduce yields by 7% for every 1 °C increase. Climate change increasing the concentration of carbon dioxide is expected to improve yields and water productivity. In this way, dry matter production and the number of panicles should increase as well as grain-filling percentage (Ziska et al 1997). However, the advantage of a high concentration of carbon dioxide can be mitigated by the increase in temperature given that a higher carbon dioxide concentration brings high temperature-induced spikelet sterility. Nighttime increases in temperature have shown negative impacts on rice yield.

More specifically, for each 1 °C increase in nighttime temperature, a decline of 10% in grain yield has been recognized.[27] Sea-level rise also constitutes an important threat to rice production, particularly in low-lying coastal areas and delta regions. In the last 15 years, the mean sea-level rise has been about 3.3 ± 0.4 mm/year and projections show that sea level may rise up to about 60 cm by 2100 due to ocean warming and glacier melting (Singh et al 2010). This will affect salinity, which is particularly relevant in parts of Australia, in the northwest Indo-Gangetic Plain, and along the African coastline, where water percolation from rice fields, by raising the water table of saline groundwater, may negatively affect nonrice crops.

Rice mostly affects the environment by liberating and capturing gases or compounds and also by modifying the characteristics of the water in rice fields. One of the most important losses from applied nitrogen fertilizer is related to ammonia volatilization. In tropical transplanted areas, losses can surpass 50%, whereas, in the case of direct-seeded rice, losses are minimal because nitrogen fertilizers are incorporated before flooding rice fields. Ammonia volatilization in lowland rice fields amounts to 5–8% of the ammonia emitted yearly globally (Kirk 2004).

In terms of greenhouse gas emissions, rice is characterized by decreasing carbon dioxide and for having low emissions of nitrous oxide and high emissions of methane. Flooded rice fields have a tendency to sequester carbon. Rice monoculture systems accumulate about 45 tons of carbon per hectare; in rotational systems, the accumulation is usually lower. For nitrous oxide, emissions are relatively low and varying across the

[27] This was found in the dry season in irrigated tropical rice (Peng et al 2004).

different rice environments. In irrigated rice fields, emissions are concentrated during the fallow period and after flooding. In rainfed fields, the aerobic accumulation of nitrate may foster remarkable emissions. Estimates for methane emissions from rice fields are from 3% to 10% of global methane emissions. This declines to 1.5% to 5% when considering the most important rice producers: China and India. However, the uncertainty around these estimates remains high (Kirk 2004). Methane emissions are mostly influenced by the management of water and organic inputs. Flooding increases the potential for methane emissions.

To prepare for climate change, intraspecific variations in yield response to changes in carbon dioxide concentration could be used to maximize the positive effects of increases in carbon dioxide. Genotypic variation in susceptibility to increases in nighttime temperature may help to develop new varieties resistant to higher temperatures. Rice varieties able to flower early in the morning can be selected in order to reduce spikelet sterility due to high daytime temperature. Considering the expected future environmental stresses on a global scale, traits of tolerance of abiotic stresses are the most important characteristics for a "virtual rice plant." By virtual rice plant, we refer to modern rice varieties currently not on the market but that could be successfully adopted in the coming years to offset climate change.

Rice vis-à-vis other crops has a wide range of adaptations as it grows in temperate, tropical, subtropical, and arid zones. This is likely to make rice able to cope more with environmental stresses than other crops. However, breeding for a virtual rice plant capable of adjusting to climate change is a necessary strategy in order to enhance productivity in addition to improving management practices. Virtual rice will need to adapt particularly to increased CO_2 concentration and rising temperature. Increased CO_2 concentration will affect the rate at which water evaporates from pores (i.e., stomatal conductance) by decreasing stomatal density and increasing water-use efficiency (WUE). This increases photosynthesis, with more rapid leaf production increasing biomass (Grashoff et al 1995). Rising temperature at the canopy level accelerates transpiration by changing the vapor pressure deficit (VPD)[28] at the leaf surface and increasing the aging of foliage, thus shortening the grain-filling period. In dry areas, this can be accompanied by water stress that can reduce spikelet fertility. In addition, because of the increased transpiration, there could be more salt uptake and impaired growth in the plant due to the accumulation of toxic ions.

Rising temperature will therefore accelerate crop development, thus decreasing water use and lowering yield and grain quality. Flowering is the most critical stage determining grain filling and this is highly dependent on daytime and nighttime temperatures. Ambient temperature above 33 °C induces spikelet sterility (Matsui et al 1997) and, as mentioned earlier, a 1 °C increase in nighttime temperature can lead to a decline of 10% in grain yield (Peng et al 2004). The simultaneous presence of high CO_2 concentration and rising temperature is likely to have more disadvantages than advantages for rice cultivation.

Therefore, it is important to trace the way to virtual rice plants that are resistant to single and multiple abiotic stresses to minimize yield losses. In the following list, we recollect information from previous sections following Singh et al (2010) depicting the awaited tolerance of abiotic stresses.

- **High-temperature tolerance**. In view of climate change, heat tolerance deserves priority. Donors have been identified, crosses made, and breeding lines are under evaluation in hot spots in different countries to identify heat-tolerant lines. To avoid a reduction in fertility due to high temperature during anthesis, early-morning flowering to escape heat has been identified in *Oryza glaberrima* and some wild species such as *O. officinalis*. Introgression lines are under evaluation to identify promising breeding lines to escape heat. Variety N22 showed tolerance of high temperature during anthesis as well as of drought (Jagadish et al 2008).
- **Salinity tolerance**. This needs to be further enhanced considering future prospects. An important QTL for salinity, called *Saltol*, has been introduced in several Asian rice varieties. *Saltol* increases salt tolerance, especially during the early seedling stage. This should be further extended to African rice varieties.
- **Drought tolerance**. This is particularly important during the flowering stage when drought may depress grain filling because of a reduction in spikelet fertility and panicle exsertion. MAS and pyramiding QTLs have great potential to enhance the drought tolerance of rice varieties.
- **Submergence tolerance**. The QTL *SUB1* has been identified on chromosome 9 and introgressed into various mega-varieties through MAS. This QTL is able to confer tolerance of submergence for 2 weeks. Work is being done at IRRI to extend the tolerance to more than 2 weeks.

Virtual rice plants should contain the proper resistances to face climate change. This consists of pooling the tolerance of various abiotic stresses in only one virtual variety. Mittler (2006) stated that tolerance of a combination of several stresses needs to be the focus for future research in order to develop varieties with enhanced tolerance of the environmental stresses that are expected to take place due to climate change. In addition, it appears from the literature that the combination of several resistances in a plant is rather unique and cannot be directly inferred from the response of plants to each individual stress. Several combinations of stresses can be envisaged and, in so doing, several virtual rice plants having dual or multiple tolerance could be developed. IRRI has developed some elite lines with dual tolerance (i.e., IR84649-81-4-B-B and IR84645-311-22-1-B) by pyramiding *Saltol* and *SUB1* QTLs using MAS and these lines are already in farmers' fields. However, in terms of virtual rice plants, we can foresee the following combinations:

[28] Per degree warming, evaporative demand is expected to increase by 5% to 6% (McKenney and Rosemberg 1993).

- Rice having yield potential of 12 t/ha in the tropics
- Dry DSR in irrigated environments in order to have more timely crop establishment with fewer problems and reduce labor costs
- Rice tolerant of salinity and high temperature
- Rice tolerant of drought and submergence
- Rice tolerant of drought and high temperature
- Rice tolerant of drought, high temperature, salinity, and submergence

The most important stresses and the related traits for improving rice yields are presented in Table 14.

Table 14. Traits for improving rice yields under various stress environments.

Trait measured	Yield potential in the tropics (12 t/ha)	Heat tolerance	Salinity	Drought tolerance	Submergence	DSR
Deep root system				X		
Root characteristics (length, secondary roots, root biomass)				X		
Faster postdrought recovery					X	
a) Maintain photosynthetic capacity						
b) Reduced senescence of leaves						
Reduced effects on pollen and spikelet fertility				X		
Phenology: days to flowering (no delays due to drought)				X		
Increased water efficiency (thicker leaves, high photosynthesis, maintain chlorophyll content, osmotic adjustment)				X		
Early-morning flowering (avoid pollen fertility and spikelet fertility problems)		X				
Increased temperature threshold for pollen and spikelet fertility		X				
Maintain test weight during high temperature and high yield		X				
Maintain high photosynthesis and high chlorophyll		X	X		X	
Maintain vegetative growth period		X				
Maintain high biomass during high temperature		X				
Net photosynthesis maintenance during high nighttime temperature		X				
Percent of survival			X		X	
Maintain starch reserve during submergence					X	
Postsubmergence recovery					X	
Less leaf damage (SES)			X			
Low Na^+ transport to shoot			X			
Preferential accumulation of Na^+ in older leaves as compared with new leaf sheaths			X			
High K^+ uptake			X			
Shoot weight reduction			X			
Yield under stress			X			
Reduction in height under stress			X			
Reduction in biomass			X			
Seed sterility (unfilled grains)			X			
High pollen fertility			X			
Good weed competitive ability						X
Early vigor						X
Lodging resistance						X
Grain yield on a par with or higher than that of transplanted rice						X
Uppermost three leaves long, erect, narrow, V-shaped	X					
Thick leaves	X					
High photosynthetic rate	X					
Early vigor	X					
Moderate tillering	X					
Lower panicle height	X					
Strong stem/lodging resistance	X					
High leaf area index	X					
Delayed leaf senescence	X					
Longer grain-filling duration	X					
Large and compact panicles	X					
Harvest index (0.50–0.55)	X					
Biomass (22–24 t/ha)	X					
Synchronous flowering (3–5 days)	X					
Na/K ratio at seedling stage			X			
Na/K ratio in flag leaf			X			
Mean tolerance index			X			
Tissue tolerance			X			
Initial seedling vigor						

Source: Own elaboration.

Conclusions

Several environmental stresses related to climate change threaten the future of rice production. The main stresses that are likely to play an important role in the coming years are increased CO_2 concentration and a rise in temperature. In addition, demand for rice is expected to increase, especially in Africa, Asia, and Latin America, because of economic growth and population increases. Currently, it is not possible, as in previous decades, to increase production through a further increase in harvested area due to the ongoing competition for land (i.e., urbanization, biofuel). Yields are stagnating in the major rice-producing areas, suggesting a lack of genetic gain in yield potential. Rice varieties with a yield advantage of about 20% over widely grown varieties under tropical conditions must be developed to achieve the target yield able to cope with climate change.

This report shed light on the opportunities for developing new modern rice varieties, so-called virtual plants. After having provided the necessary breeding background and technical methodology available, abiotic and biotic stresses have been considered, showing the state of the art in this field of research. To achieve yield potential, the crop must also be optimally supplied with water and nutrients and completely protected against weeds, pests, diseases, and other factors that may reduce growth. Management practices were considered as well as dry direct-seeded rice in order to have more prompt crop establishment and fewer labor-intensive requirements for rice production. To meet the nutritional needs of an increasing population, it will be important to promote new investments for agricultural research in order to further develop new modern rice varieties containing dual or multiple resistance to environmental stresses. Currently, the emphasis is on breeding varieties containing two or more resistances such as resistance to salinity and high temperature, resistance to drought and submergence, and resistance to drought and high temperature. An ideal super virtual variety would be one incorporating resistance to drought, high temperature, salinity, and submergence in only one rice variety. The report finishes by presenting several key potential traits that characterize the virtual rice plants in the pipeline. Translating those traits into crop models should allow us to understand the yield potential of these new virtual crops in different agroecologies that face different environmental stresses.

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IRRI
INTERNATIONAL RICE RESEARCH INSTITUTE
DAPO Box 7777, Metro Manila, Philippines