World rice production: main issues and technical possibilities

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in

Chataigner J. (ed.).
Activités de recherche sur le riz en climat méditerranéen

Montpellier : CIHEAM
Cahiers Options Méditerranéennes; n. 24(2)

1997
pages 57-69

World rice production main issues and technical possibilities

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Résumé. *Les principaux problèmes et les possibilités techniques de la production mondiale de riz font l'objet d'un rapport comparatif. Pour les chercheurs et pour la production rizicole mondiale, il s'agit avant tout de trouver des solutions appropriées à de grands problèmes, comme les basses températures, l'utilisation efficace de l'eau, sa disponibilité et sa pollution, les contraintes relatives aux terres, les grandes entraves biotiques (pyriculariose, pourriture de la tige, mauvaises herbes, riz rouge...), les écarts de rendement, l'amélioration du rendement, la qualité du riz, la réduction des coûts élevés de production et la promotion d'un flux d'informations sur le riz. Actuellement, parmi les technologies nouvelles étudiées et/ou testées, on signale le riz hybride, de nouveaux types de riz (le «super riz», une variété à panicule moins haut), les feuilles en V et les biotechnologies. La Consultation technique a recommandé :*

– de réduire l'écart entre le rendement potentiel et le rendement réel en adoptant une stratégie intégrant recherche, vulgarisation, institutions et politiques gouvernementales appropriées en matière de riz ;

– de promouvoir une collaboration interrégionale et internationale en matière de recherche sur le riz et ses principaux problèmes, par exemple les basses températures, la pourriture de la tige, le riz rouge, les écarts de rendement et les coûts de production élevés ;

– de mettre au point de nouvelles méthodes pour l'amélioration génétique ainsi que des façons culturales appropriées pour une utilisation plus efficace de l'eau dans la production rizicole ; et

– de favoriser un flux d'informations sur le riz au moyen de publications et en recourant au courrier électronique pour de brèves conférences sur des questions concernant le riz.

Abstract. Rice is the most economically important food crop in many developing countries, and has also become a major crop in many developed countries where its consumption has increased considerably, particularly in North America and the European Union (EU) due to food diversification and immigration. It has become necessary to meet the demand of the world's current population growth rate, and the least costly means for achieving this aim is to increase rice productivity, wherever possible. Many rice-producing countries still have a large gap between their present and potential yield. Therefore, efforts should be focused on identifying the causes of this gap, especially in the production factors and various features of crop management.

The main challenge encountered by scientists involved in rice research and production in the world is to find appropriate solutions for major issues such as low temperature in the temperate areas, problems of water use efficiency, availability and pollution, land constraints, major biotic stresses, improvement of rice yield, with emphasis on bridging yield gaps, raising yield ceiling and reversing yield decline, rice quality, decline in investment for increased rice production, high costs of production and the flow of rice information.

At present, some emergent new technologies including hybrid rice, new plant types ('super rice' type and lowering panicle height type), V-type leaves concept, and rice biotechnologies for increasing rice production have been seriously studied and developed. As the rice area worldwide has remained more or less stable since the early 1980s, and a trend to increase this area is unlikely in the future, it is believed that the hybrid rice technology and new plant types of rice, which are aimed to increase rice productivity, will play an important role to meet the world's rice demands in the coming century.

As financial and human resources are limited in many countries, regional, interregional and international collaboration and cooperation in rice research should offer practical solutions for increased food in the world. Furthermore, collaborative efforts oriented towards strengthening the flow of rice information—through the existing modern computerized communication facilities—among Mediterranean member countries, international institutions, universities and others working on rice in the temperate regions, should be particularly encouraged.

Introduction

Rice is by far the most economically important food crop in many developing countries, providing two thirds of the calory intake of more than 3 billion people in Asia, and one third of the calory intake of nearly 1.5 billion people in Africa and Latin America (FAO, 1995a). Recently, in several developed countries such as North America and European Union (EU), rice consumption has increased due to food diversification and immigration. In the last two decades (1970-90), the per capita rice consumption increased at various rates, ranging from 2.4 percent/year in Italy to 8.2 percent/year in UK (Faure and Mazaud, 1996). The present high population pressure, the high costs of production and the demands for income improvement have encouraged rice growers to increase yield and crop intensity on limited lands, e.g. high land productivity, in order to produce adequate food for the world.

However, recent observations of the stagnant or even declining yields, land degradation and environmental pollution in some irrigated areas have raised concern regarding the long-term sustainability of such production and productivity. Nevertheless, the world's rice production still has space for improvement, through increasing land productivity and raising its yield potential. In fact, large yield gaps, which are still common on farmers' fields, need to be improved, even though these have decreased gradually in the developed countries.

The main challenge for rice research and development in the world—which includes improvement of the small farmers' welfare and rural employment on a sustainable and economic basis—is to find ways and means to produce more food for the fast growing population with limited land, less labour, less water and even less chemical inputs as well as to improve.

I – World rice productions vs. temperate rice

In 1994, about 146.5 million hectares of rice were harvested in 107 countries, producing approximately 534.7 million tons of paddy, which is 1.16 times the amount produced in 1984. In order to feed the increasing global population, the world's annual paddy rice production must increase from the present level to 690 million tons by the year 2010 (or 27.6 percent) (FAO, 1993). However, the world's annual production growth rate has recently declined. It was 2.7 percent in the 1964-1974 period, 4.0 percent in 1974-84 and only 1.5 percent in 1984-94.

Asia accounts for 90% of the world's production and consumption of rice because of its favourable warm and humid climate, but suitable lands for increasing rice production are almost exhausted. In Africa, the economic importance of rice has steadily increased over the last two decades. The amount imported has more than doubled following the gradual evolution which has taken place in the nutritional habits of many Africans, especially those living in the urban areas—which has changed from eating only traditional foods, such as cassava, millet and sorghum to rice and wheat. The per capita rice consumption has grown from 14.8 kg/year to 16.3 kg/year for the period 1980-1992. In Latin America and the Caribbean, rice production has increased by 32 percent in the last decade (1983-93) and also here the per capita rice consumption has increased from 25.8 to 26.3 kg/year (FAO, 1995a).

Temperate rice (mainly japonica) commonly grows well in the temperate regions and sub-temperate regions, but it is also found in Mediterranean climate zones like: Egypt, Morocco, Turkey, etc., in high altitude areas: Nepal, Bhutan (Asia), Rwanda, Burundi (Africa), and in the Southern Cone of Latin America: Chile, Argentina, etc. From 1982 to 1994, the temperate rice area has not changed much, but its production increased by 16.6 percent, mainly due to the yield increase from 5 to 5.8 t/ha (Table 1). Because of the favourable climate in the temperate regions and Mediterranean climate zones, Japonica rice yield is usually superior to that of Indica rice grown in humid tropical regions. Considerable national efforts have been dedicated to strategic and applied research on temperate rice, however the international work on the same rice has not yet been well coordinated.

Climatic constraints and socio-economic factors are the main limitations to the area expansion of japonica rice. Low temperature and water availability are the limiting factors for growing japonica rice inside and outside temperate regions. Low temperature below the critical point can affect seedling establishment in the early growth stage and high grain sterility in the late crop season. Unavailability of water has impeded farmers from growing rice in the southern part of California as well as in southern Italy, even though these areas are more favourable in terms of climate for growing rice than the northern parts of the countries. The developed countries' subsidy policies have maintained actual area of rice production in the temperate regions. A reduction or abolition of subsidies and protection policies would completely change the current production of Japonica rice and the world's rice trade situation. This trend could be anticipated as GATT goes into real effects (Tran, 1994).

Table 1. Area, yield and production of temperate rice in the world in 1982 and 1994

Country	1982 Area (x 1000 ha)	1982 Production (x 1000 t)	1994 Area (x 1000 ha)	1994 Yield (t/ha)	1994 Production (x 1000 t)
AMERICA	**2,556**	**12,510**	**2,865**	**5.7**	**16,473**
USA	1,320	6,969	1,336	6.7	8,972
Chile	37	131	30	4.5	133
Uruguay	69	419	134	5.5	680
Paraguay	26	54	24	3.4	82
Argentina	114	437	141	4.3	606
Southern Brazil*	1,000	4,500	1,200	5.0	6,000
EUROPE	**1,088**	**4,726**	**1,024**	**4.2**	**4,324**
Albania	4	12	1	4.1	4
Bulgaria	16	75	1	2.9	3
France	5	27	27	4.5	124
Greece	16	83	15	8.0	120
Hungary	13	48	5	2.8	14
Italy	177	1,008	238	5.5	1,324
Portugal	34	143	22	5.2	115
Romania	21	46	5	3.1	14
Spain	68	402	63	6.2	390
Turkey	77	350	40	5.0	200
Yugoslavia, SFR	9	32			
Macedonia, FYR			2	5.0	10
Former USSR	648	2,500	605	3.3	2,006
NORTH AFRICA	**432**	**2,445**	**590**	**7.9**	**4,652**
Egypt	431	2,441	579	6.5	70
Morocco	1	4	11	6.5	70
NEAR EAST	**541**	**1,768**	**710**	**4.1**	**2,920**
Iran	483	1,605	620	4.3	2,700
Iraq	58	163	90	2.4	220
EAST ASIA	**12,255**	**65,146**	**11,972**	**5.9**	**70,536**
Korea DPR	810	5,000	600	3.5	2,104
Korea Rep.	1,188	7,308	1,160	6.1	7,056
Japan	2,257	12,838	2,212	6.7	14,976
Northern China*	8,000	40,000	8,000	5.8	46,400
AUSTRALIA	**123**	**854**	**122**	**8.3**	**1,017**
OTHERS*			**12**	**2.5**	**30**
WORLD (Temperate)	**17,005**	**85,681**	**17,295**	**5.8**	**99,952**
World rice	**141,886**	**424,362**	**46,452**	**3.6**	**534,701**

* Estimated.
Source: *FAO Production Yearbook,* 1984 and 1994.

II – Challenges for rice research and production

The extensive adoption of modern and improved production technology was accelerated through favourable government policy, expansion of irrigated areas, accessibility to agricultural credit, intensive extension services and the availability of agro-chemicals, especially fertilizers and herbicides. The Green Revolution in the 70s and 80s has maintained rice production well ahead of the population growth in many developing countries. Concern has increased about “mining” the soil for plant nutrients, changes in the status of rice pests from minor to major economic importance, a negative impact on the environment and losses of natural resources and biodiversity (Shastry et al., 1996).

Major issues on rice production over the world were commonly reported, as follows:

1. Low temperature

Low temperature is the greatest concern of rice growers in the temperate regions. Although farmers have tried to deploy varieties with tolerance to low temperature and recommended cultural practices, such as planting date and water depth during panicle development, rice crops still suffer from poor establishment and high grain sterility, due to variable climate every year. In 1993, the average night temperature went down to about 11°C in the summer causing heavy losses in Italy, and particularly in Japan and the Republics of Korea. Japan had a subsequent shortage of rice, and had to import approximately 2 million tons of milled rice in 1994-95.

It is well known that japonica rice is, to some extent, tolerant to cold. However it is less productive if it grows under very low temperature. The critical temperature of rice is around 15°C depending on the varieties. The rice-growing countries in the temperate regions devote their major resource for varietal improvement in this regard. Recent breeding work has focused on cold tolerance, improving seedling vigour, and reducing floret sterility of rice. Date of planting, early-maturing cultivar, and maintaining high water depth during the panicle development could help the rice crops escape from cold.

Farmers, however, still need additional varieties with higher cold tolerance. More strategic research is still required in this field. The biotechnological approach should be more deployed towards identifying high cold tolerance gene from rice or others. Rice growers should be aware of the newly-developed varieties and emerging proven technologies and need to be trained in this area.

2. Water problems

Water is the primary factor determining the success of the rice crop. As mentioned earlier, the Green Revolution has bypassed Sub-Saharan Africa, due to, among other factors, inadequate irrigation and drainage development. Wetlands have been widely exploited for rice production in many parts of the world. Many problems relating to this matter are well known: water efficiency, water availability and water quality.

A. Water efficiency

Water is a critical and the most important factor in rice production. About 55 percent of the areas cultivated to rice are under irrigation. It is known that in irrigated systems, more than 4-5,000 litres of water are used to produce 1 kg of rice in many areas. Field level assessment suggests a water efficiency of 50 percent and it may reach 80 percent if drained water could be recycled and used (CGIAR, 1996a). The costs of developing new areas under irrigation and rehabilitation of large-scale irrigation schemes are high. It is therefore important to improve water use efficiency in rice production systems through the use of appropriate water control and crop management techniques, with emphasis on irrigation technologies combined with genetic improvement. At present, the improvement of water use efficiency has drawn little attention from rice breeders.

B. Water availability

Although water in South-east Asia is usually considered abundant, particularly in the monsoon rainy season, it is predicted that many Asian countries will suffer from water shortage by 2025, as the rate of population and urbanization growth is rapidly increasing. According to Feder and Keck (in Pingali, 1996), the per capita availability of water declined of 40-60 percent over the period 1955-1990. The competition related to the demand for water between agriculture and other sectors such as industry, environment, has become acute. Alternative agricultural genetic improvement, appropriate cultural techniques and efficient irrigation systems should be developed to solve this problem.

C. Water quality

Poor drainage is the major factor connected to water problems including waterlogging, salinity, toxicity and water pollution. This poor drainage situation is mainly due to inappropriate development of irrigation schemes and passive reaction of farmers to the schemes' operating organization and their economic conditions. Salinity is caused by saline water intrusion from the sea in the coastal regions and by the upward movement of salt-water through capillary action in soils, and salt accumulation on the soil surface due to fast evaporation. About 24 percent of the irrigated lands have been affected by salinity problems (Postel, 1989).

3. Land constraints

A. Marginal lands

In Asia, during the Green Revolution, the rapid expansion of modern rice varieties has exhausted favourable lands. By 2025, 53 percent of the people in Asia will live in urban areas compared to 30 the percent in 1990 (communication with Dr. M. Hossain, IRRI, 1995). Fast urbanization, industrialization and the demographic pressure have encouraged farmers to exploit marginal lands for increased rice production to meet their family's demands. Therefore, acid soils, tidal lands, forest lands, etc., have been reclaimed and brought under cultivation, thereby limiting crop yield potential. In intensive irrigated rice farming systems, the major soil problems include change in soil characteristics, soil mining affects and soil pollution.

B. Change in soil characteristics

Long-term soil puddling and drying lead to the formation of hard pans 5-15 cm below the surface. The hard pan, which has a bulk soil density with less medium and large pores, reduces the soil permeability, and the root ability to extract nutrients from subsoils, and increases the formation of soil toxicities due to long waterlogging condition, thereby hindering the growth of dryland crops after rice. The widespread of modern rice also encourages the increased utilization of machinery in rice farming, particularly in rice-producing developed countries, which in turn induces soil compaction.

Permanent waterlogging and rice monoculture have commonly caused microelement deficiencies, especially zinc and sulphur, and toxicities, notably iron. Zinc deficiency is the most widespread microelement disorder of wetland rice. Zinc deficiency can be observed under one or more of the following soil characteristics: high pH, high organic matter content, high available P or Si, high Mg/Ca ratio, and low available Zn (Ponamperuma and Deturck, 1993). The symptom of Zn deficiency has increasingly been reported from India, Bangladesh, Pakistan, the Philippines, Thailand and the United States.

In Asia, increased use of low-S concentrated fertilizers and high intensive-rice cropping has caused S deficiency (Ponnamperuma and Deturck, 1993). Sulphur deficiency has been reported from Bangladesh, Indonesia, Nigeria and Brazil. Iron toxicity is commonly found in continuously flooded soils. Other toxicities, such as boron, salinity have been reported in the poor-quality irrigation.

C. Mining effects and fertility change

Modern rice varieties exhaust soil fertility more rapidly than traditional varieties. Modern rice crops under intensive cropping (about 6 t/ha) remove from soils 100 kgN, 50 kgP_2O_5, 160 kgK_2O, 19 kgCa, 20 kgMg, 10 kgS, 0.6 kgFe, 0.19 kgZn, 0,64 kgMn, 0.08 kgCu, 0.06 kgB, and 0.004 kgMo per hectare per growing season. Farmers usually compensate these nutritional losses, especially macro-elements, with chemical fertilizers while neglecting some essential micro-elements. In the long run, the micro-elements become deficient and cause an imbalance in soil nutrition, increase demand for phosphorus and potassium and cause nitrogen inefficiency, affecting the ultimate grain yield. Therefore, the soil nutritional status requires periodic monitoring, particularly for intensive cropping systems (Tran and Ton That, 1994).

D. Environmental problems

The flooded rice field has a high potential to produce methane while the potential of upland rice for methane production is not significant since upland rice is never flooded for a long period of time. The hydromorphic rice produces methane emission when the soils are flooded and no methane under the dry soil condition. The irrigated rice may cause problems of waterlogging, ground water depletion, salinity and alkalinity. Upland rice may increase deforestation and soil erosion if the fallow period is short.

Fertilizer application (especially N), may contribute to greenhouse gas emission, due to the potential losses of applied nitrogen, as nitrous oxide. The impact of nitrous oxide on global warming is large compared to carbon dioxide with a ratio of 180-300/1. The excessive use of fertilizers and pesticides in rice production may cause water pollution and health hazards through drained water.

The above-mentioned land problems could contribute to the low rice productivity. Some phenomena, such as soil mining, exhaustion, exploitation of marginal lands, imbalanced soil nutrition and intensive cropping systems, deserve to receive more consideration to avoid the decline in productivity. However, under the high population pressure, farmers are urged to increase yield through crop intensity on less lands, e.g. high land productivity in order to produce adequate foods for the mankind. Thus, the intensive farming systems have to be conducted by small-scale farmers, who are short of skill, unaffordable in farm investments and unaware of environmental consequences. Farmers' skills and technical knowledge should be improved through frequent training and field visits. Some delivery services, such as extension work, credit provision, appropriate input deliveries, farmer organizations, cooperative and marketing should be made available to farmers in supporting the intensive farming systems. These conditions are still shortcoming in developing countries. Apparently holistic approaches are required to ensure and sustain high productivity and production in the long-run.

4. Biotic stresses

In the humid tropics, the introduction of semi-dwarf-stature varieties and the large use of nitrogen fertilizers and insecticides have changed the status of pests from low to high related to the economic importance in rice production. It was reported the serious incidence of some insects such as brown plant hoppers, stem borers, leaf folders, etc., and diseases such as blast, bacterial blight, sheath rot... The short growth duration of modern rice varieties has modified existing cropping patterns and increased farming intensity from single crop to double or triple crops, thereby inducing a favourable environment for insect pests and pathogen multiplication.

In the temperate regions, diseases and insect pests are less problematical than those in the humid tropics, due to its favourable climate (dry climate and relatively low night temperature in the Summer) and single rice cropping per year. However, some diseases such as blast, stem rot (*Sclerotium oryzae* Catteneo) and sheath spot (*Rhizoctonia oryzae-sativae*) and major insects, such as rice water weevil (*Lissorhoptus oryzophilus*) are commonly reported in this climate. Breeding efforts and agronomic management are explored to help minimize these problems.

Rice growers are particularly attentive to weed control. In the temperate regions, major weeds includes barnyard grass *(Echinochloa spp.), Cyperus spp., Alisma spp., Sagisttaria spp.,* wild rice, etc. The infestation of red rice in continuous rice production systems using direct seeding as method of crop establishment is commonly reported. Several weed control methods, such as agronomic practices (good seed sources, high seed rates and water depth), herbicides, mycoherbicide, allelopathy selection and gene engineering have been explored. According to Hill et al. (1994), the herbicide use will be reduced in future, as a result of water pollution, affects on adjacent sensitive crops, costly aquatic systems and weed resistance. Integrated weed management strategies, together with better information on weed control, are suggested for weed problems in the temperate regions.

Considerable research efforts are still needed to solve the above problems. However, some intractable constraints in biotic and abiotic, such as low temperature, drought, flooding, blast, bacterial leaf blight, yellow stem borers, weed resistance, etc., need more upstream research, particularly in the physiology and biotechnology to understand and solve the problems.

5. Improvement of rice yield

Productivity of rice does not only vary between one country and another, but also within the same country based on the different agro-ecological zones and production systems used. The gap between the farmers' yields and those obtained by research stations is still large, even though some reduction has been reported recently. This Indicates the various limiting factors affecting rice productivity and production, ranging from land development, production and marketing.

A. Yield gap

In irrigated rice, the farmers' average yield is approximately 4 to 8 t/ha, compared to the 7-13 t/ha obtained by the research stations. It is noted that the average yield in California and Australia is higher than that in EU by 30-40 percent. In fact, it was reported that the state rice yield in California was 8 500 lb/acre on 485 000 acres in 1994 (Rice Experiment Station, 1995). In Australia, the average yield reached 8.5 t/ha in 1995 (FAO, 1995b). Is it possible for the rice yield in the EU to catch up the yield level of the above state and country under the Mediterranean climatic conditions?

Closing these gaps is not an easy task, and the yield gaps still exist in all rice-producing country. It requires the concerted efforts, from governments' rice policies to ensuring appropriate land levelling, efficient water control, appropriate inputs (improved seeds, fertilizers, pesticides) supplies, credit provision, and effective institutional supports (research, extension, marketing, incentive rice price). If one of these is missing or inappropriate, the yield gap cannot be effectively closed.

Consequently, understanding of the various components of grain yield of rice and how to improve them will help improve manpower skills and capability in increasing rice production by raising the current yield level. According to Lacy (1984), the 'Ricecheck' method in Australia, which was developed for wheat in 1984, and subsequently applied to rice in 1986, has played an important role in increasing rice yield over the last 5 years. The 'Ricecheck' is the integrated objective management package, which provides the blueprint for obtaining the goal of 10 t/ha, through discussion groups and the participation of rice growers in field activities: observing, measuring, recording, interpretating and acting.

The 'Ricecheck' concept consists of seven points relating to yield:

1) "Develop a good field layout,
2) Use the recommended sowing dates,
3) Obtain good and economic weed control,
4) Establish a seedling population of 150-300 plants/m2,
5) Achieve 500-1100 tillers/m2 at panicle initiation and NIR tissue nitrogen content of 1.2-2.2 percent,
6) Topdress nitrogen based on tiller counts and NIR tissue analysis using the PI Nitrogen Test, and
7) Achieve, at an early pollen microspore, a water depth of 20-25 cm, depending on variety".

B. Yield plateau

The yield potential of modern rice varieties has reached the plateau. Maximum yields are about 13 t/ha in tropical environments and 15 t/ha in temperate regions. The higher yield of the latter is due to the more favourable climatic conditions, such as long day-length, high solar radiation and low night temperature. In the tropical climate, the yield per season of IR 8 has still been championed, while yield per day has increased by the development of early-maturing modern rice varieties. The genetic resistance and tolerance to adverse environments, coupled with improved agronomic techniques from the start of rice planting to post-harvesting could raise the present country yield. The present technology of hybrid rice increases the rice yield potential by 15-20 percent. IRRI has developed a new plant type of rice (or 'Super rice'), aimed to raise yield potential by 50 percent. More discussions on hybrid rice and 'Super rice' will be made below.

C. Yield decline

Yield decline in rice has been found at various IRRI experimental farms and at some research locations in the Philippines. In the sixties, rice yield reached 8-9 t/ha at the IRRI farm, but recently it has not exceeded 6-7 t/ha in the dry season and 5-6 t/ha in the wet season, while the fertilizer rate remained constant. In three locations in the Philippines, rice yields have declined by 0.1 to 0.3 t/ha per year over a 20-year period (De Datta, 1989). IRRI's long-term fertility experiments on two or three irrigated rice crops per year, over the last 25 years, Indicate some yield decline at many of its research sites (Cassman and Pingali, 1994). The causes of the yield decline phenomenon at the research stations are under investigation. It has not yet been ascertained if such productivity declining phenomena are restricted to a few research farms or are common in all research farms regardless of the degree of intensification in rice cropping.

At the farmers' fields, a declining factor by farmers who grow modern varieties, was observed. It is well known that modern technologies are very sensitive to different crop management levels. In the Chiang Mai Valley in Thailand, yield declined from 7 to 4 t/ha under normal crop management for unknown reasons (Gypmantasiri et al., 1980). In Africa, several rice development schemes usually achieved the highest yields in the early years, but subsequently the yields began to decline possibly as a result of inappropriate farming, including the use of poor seeds sources, unreliable input (fertilizers) supplies, poor crop protection, poor water management and soil nutrition depletion. A decline in productivity was also found in the rice-wheat production system, which accounts for more than 11 million hectares of intensive food production in South Asia.

The decline in yield on farmers' fields has not yet been thoroughly studied and documented. It is noted that farmers are now using more numbers and higher levels of inputs than before to maintain the rice productivity. How can we minimize the problem and sustain long-term production? Can we maximize and sustain long-term high productivity of rice (for example: 'Super rice') and at the same time reduce production costs? and how? Is there a need for an early-warning system for yield decline in the world? If affirmative, what would such a system look like?

6. Rice quality

Rice consumption has increased in Europe, America and Africa as a result of food diversification and immigration (North America and European Union). Recently, the demand for long grain and aromatic rice has been increasing in North America and EU, resulting in a significant change in rice-planted areas. According to Faure and Mazaud (1996), in Italy, the round grain type declined from 70 percent of cultivated areas in 1940s to 12 percent in 1989-90. In France, 65 percent of round grain type in 1980 decreased to 15 percent in 1993. This has been resulted due to EU's incentive programme for Indica-type rices. The yield of Indica rices is lower than that of Japonica by 0.5-1 tonne/ha in the temperate regions and milling yield is only 58 percent as compared to 61-62 percent for medium or round grains.

Many long grain varieties have been developed for temperate conditions, particularly under frequent low night temperature, where grain quality still needs to be improved. The Basmati rice types, which have high grain quality with relatively-long grain and aromatic characters and long extruded cook grains, still needs to be developed, with yield improvement. Special rices such as waxy rice, organic rice and natural (wild) rice have recently drawn rice growers's particular attention to some rice-producing countries. Milling yield and cooking quality and processing characteristics need further studies. Harmonization of analytical methods for grain quality at national and international laboratories should be encouraged.

7. Decline in investments for increased rice production

Water control was the main factor necessary to increase the rice production and productivity in Asia during the Green Revolution, but a decline in investment for the development of irrigation infrastructures in many developing countries has taken place, thereby affecting the growth of rice production as well as productivity. In Asia, the irrigation investment has declined by about 60 percent since the 1960s (Pingali, 1996). The amount loaned for irrigation development decreased from $630 million in 1977-79 to $202 million in 1986-87 (Rosegrant and Pingali, 1993). Likewise, the growth rate in research expenditure in Asia declined from 7.4 percent in 1961 to about 4.6 percent during the 1980s (Rosegrant and Pingali, 1993).

8. High costs of rice production

High labour costs, mechanization, the use of chemical inputs and the slow increase in grain yield contributed to the high cost of rice production in irrigated rice, especially in developed countries. The cost of rice production was around US$ 400/tonne in France (Cambon, 1995) and US$ 166/tonne in the USA (Sanint and Zeigler, 1990). Subsidy has become the national policy in many countries. It is known that an increase in rice yield can substantially compensate for the high cost of production, but it increases slowly and cannot catch up with the latter. In addition, the yield potential has reached the plateau and the price of rice is not sufficiently high to provide farmers with an incentive for increased production. The world's price of rice declined during the 1980s, however, recently it has again increased and levelled off, due to the increased import of rice from China, Indonesia, Philippines, etc. and the occurrence of flooding and drought in these countries.

9. Rice information

One of the most effective means to promote the flow of agricultural information over the world is the modern computerized communication facilities, which allow to gather, disseminate, and facilitate interaction and exchange of such information among a large number of people and institutions working in the same field. Obviously, it still needs to have initiatives, coordination and leadership in this regard. The Inter-Regional Cooperative Research Network on Rice in the Mediterranean areas have regularly published the *MEDORYZAE* Bulletin, which provides member countries with interesting news on its activities concerning technical and managerial issues in the Network. More collaborative efforts among member countries and institutions, universities, NARCs, etc., working on rice in the temperate regions should be encouraged in the participation in the flow of rice information in various disciplines. At the initial step, e-mail and other electronic mail forum for short-term conferences on relevant topics could be explored to promote the flow of rice information among those interested.

III – Emergent new technologies for increasing rice productivity

1. Hybrid rice

Recently, hybrid rice is the only emergent technology available for raising the ceiling of rice yield potential by 15-20 percent. Hybrid rice, which is grown on 17 million ha and accounts for more than 50 percent of the total rice area in China, has helped this country to produce additional 300 million tonnes of rice since 1976 and has saved more than 2 million ha for agricultural diversification. This was achieved due to the fact that the yield of hybrid rice is more than 20 per cent (or 1 to 2 tons/ha) higher than that of conventional varieties (Yuan and Fu, 1995). This technology is very essential for highly populated areas, where arable lands are limited.

Furthermore, this practice to increase rice production involves less investment than land and irrigation development; however, the present method of hybrid seed production (three-line) is still labour-intensive and costly. The new method of deploying two-line hybrid rice by using environment-sensitive genetic male sterile lines (temperature and photoperiod) seems promising for the future wide adoption of hybrid rice in other countries besides China, India and Vietnam.

The one-way method or apomixis of rice is under intensive research in China, the USA and at IRRI in the Philippines, but no success in this field has yet been reported. At CIMMYT in Mexico, Savidan and his team are working on the development of apomictic maize, exploring combined conventional breeding techniques, DNA markers and other advanced science (CGIAR, 1996b). Once a maize apomictic gene is identified it could be transferred into other crops including rice. As apomictic seed reproduces asexuality, farmers do not need to renew their seeds, especially in hybrid rice seeds.

FAO has assisted several countries in Asia (India, Vietnam, Bangladesh and Myanmar) and Latin America (Colombia and Brazil) in strengthening their national capacity for the development and use of hybrid rice, through the FAO Regular Programme, TCP funding (Vietnam and Myanmar), and UNDP project (India). India has recently released 4 hybrid rice varieties and Indian farmers have, for the first time, grown 6,000 ha of hybrid rice in 1994, followed by approximately 80,000 ha in 1995. Vietnam grew 11,000 ha of hybrid rice in 1992 and around 100,000 ha in 1995/96, mainly with Chinese seed imported through border trade. Under the present demographic pressure and limited arable land, an increase in rice productivity through the hybrid rice method, will contribute to the world's food security.

It is also noted that FAO and IRRI have jointly established the International Task-Force on Hybrid Rice (INTAFOHR) in 1995, with the participation of 12 member countries, aimed at expediting the development and use of hybrid rice outside China. Its Coordinating centre is located at IRRI in the Philippines.

2. 'Super rice'

The yield of rice has increased during the last two decades and has now reached plateau. The variety IR 8 which was released by IRRI in 1966, still has the highest yield potential (10-11 T/ha) against the other improved varieties, recently introduced to farmers in Asia. Rice scientists have been working towards raising the present yield level to 15 t/ha or more by making carbohydrate partitioning more efficient for increasing grain yield (sink size) or harvest index. The work on super rice initiated in 1988 by IRRI, with studies on improvement of physiological aspects of modern rice for increasing yield potential. The potential yield of this rice could reach 15 t/ha under tropical conditions, compared to the present potential yield of 10 t/ha. According to a forecast made by IRRI's rice breeders, seeds of super rice will be available to farmers within 5-6 years. At present, several promising lines with high yield have been developed, but they are susceptible to brown plant hoppers, and have low percentage of filled grains and low grain quality. Some scientists, however, are still sceptical about the productivity, sustainability and environmental impact of super rice.

Super rice is the continuation of the modern rice generation, which was widely adopted by farmers during the Green Revolution. Genetically, to achieve the goal of 15 t/ha, IRRI has exploited two strategies of breeding, e.g. crossing tropical Japonica x Indica and then deploying heterosis of hybrid rice technology. The first strategy would increase the present yield potential by 25% (from 10 to 12.5 t/ha), while the second strategy would further increase the yield by 25% (from 12.5 to 15 t/ha). Rice scientists are now hoping to raise HI of HYV to around 0.60 ('Super Rice'), through a "new plant type" concept including reduced tillering, large panicles, high grain density, longer grain filling period and resistance to major pests (Khush, 1995).

Physiologically, high-density grains were conceptualized and designed by IRRI. After six years of work in the Philippines, it proposed a new approach to increase grain yield by increasing weight per grain within a variety through a change in plant type (Vergara et al., 1991). High density (HD) grains have higher grain volume, weight, milling yield and head rice recovery.

A new plant type, that was proposed by IRRI to have HD grains is described as follows:

1) "**Low tillering**, to produce vigorous and large tillers that result in more HD grains;
2) **Panicle weight type**, to produce large panicles with mostly primary branches;
3) Panicles composed mainly of **primary branches** as they have mostly HD grains and fewer empty and half-filled spikelets;
4) **Large pedicellar vascular bundle** for better transport of assimilates;
5) **Thick culm** for more vascular bundle, less tendency to lodge, better support of panicle, and probably a larger area for carbohydrate accumulation;
6) **Medium-size grains**, since large grains have low density and are not usually completely filled;
7) **Erect and thick leaves**, for better light distribution and higher photosynthetic rate per unit leaf area;
8) **Dark green sheath for the flag leaf** to increase assimilate production;
9) **Slow senescence** for increased assimilate production and a longer grain-filling period;
10) **High photosynthetic rates** and **low photosynthetically-active radiation**, so that carbohydrate supply will be less limiting during the wet season;
11) **Medium growth duration** for carbohydrate accumulation before heading; and
12) **Intermediate plant height** with an HI of 0.55, because semi-dwarf plants tend to be high tillering".

A similar concept has been adopted for rice production under direct seeding in the temperate zone and others related. Most improved varieties grown in these countries have medium growth duration, less tillering, panicle-weight type, medium-size grains, less grain number per panicle, etc.

3. Lowering panicle height

This is another IRRI's findings while making efforts in increasing rice yield potential by 50 percent or 15 t/ha (CGIAR, 1996b). Lowering panicle height may increase photosynthesis by 20-40 percent as the panicles are no longer shaded by the leaves. This finding was proved by IRRI scientists by exploring different techniques from removing panicles completely from grains to reduce panicle heights, to using hormones to change the panicle height. A simulation approach has demonstrated that reducing panicle height from 70 to 50 cm would cause no more lodging and would increase yield by 50 percent. This concept may not require more nitrogen to increase yield, e.g. increased nitrogen use efficiency, as a result of increased photosynthetic capacity of rice plant.

4. V-type leaves

Besides the work done by IRRI's scientists, Chinese and Japanese scientists have worked on super rice in the last several years. Chinese scientists have developed "New HYV" or super HYV, such as Teging, Shanshua, etc., with high yield potential. Japan started a 15-year project (1981-95) to increase the HYV yield by 50 percent. The yield of the variety Oochikara with large grains, which has been developed, is higher than the control by 15-20 percent. This variety is not suitable for human's daily diet, but for animal feeding or others (Takita, 1994).

Japanese scientists proposed a new model of V-type leaf plant, in which half of the leaf's angle from the horizontal plane should vary from 35 to 52 degrees. The photosynthetic rate of unfolded V-type single leaves was the same with a reference cultivar and parents, but their leaf thickness and nitrogen content were higher and leaf area was less by 18-38 % (Sasahara et al., 1992). The high yield (13-15 T/ha) of V-type cultivars is attributed by five features, as follows:

1) Mutual shading decreased as a result of leaf blade's inclination;
2) Lower leaves received more irradiation;
3) The photosynthetic rate unchanged although leaf inclination;
4) Higher leaf thickness and nitrogen content; and
5) High root activities.

The character of V-type leaf is controlled by a recessive gene. As grain quality is poor, V-type rice plants were evaluated for feed and fodder use (Sasahara et al., 1992).

As the rice area worldwide has remained more or less stable since the early 1980s and a trend to increase it is unlikely in the future, it is believed that the hybrid rice technology and the new plant type rice, which are aimed to increase rice yield, will play an important role to meet the world's rice demands in the coming century.

5. Biotechnology

Considerable progress has been made toward this new frontier upstream rice research programme, particularly on the genetic engineering of rice for resistance to brown plant hoppers, yellow stem borers, tungro virus, rice ragged stunt virus, bacterial leaf blight, and sheath blight. IRRI has worked on Bt toxin gene and coat protein gene for ragged stunt virus, gene for submergence tolerance, gene for controlling CMS lines and nitrogen-fixing genes for rice plants. It is worthy to note that Dr. Yukoh Hiei and his colleagues in Japan, for the first time, have developed an efficient transformation method for Japonica rice by *Agrobacterium*-mediated system using rice scutellum-derived calli (Hiei and Komari, 1995). However, techniques and approaches to molecular breeding still need to be perfected to make them more efficient, accurate and less costly, especially for Indica rice. Scientists have made great contributions towards the development of innovative technologies of rice, but the concrete outcome of these efforts will be seen at the beginning of the next century.

IV – Conclusion

An increase in rice production should meet the demand of the world's current population growth rate. A less costly means to achieve this aim is to increase rice productivity, wherever possible. Many rice-producing countries, even in the developed countries, still show a big gap between the present and potential yield. Hence, efforts should be focused on identifying the causes of this gap, especially in the production factors and the various features of crop management. An adequate understanding of physiological aspects of rice productivity and its components will facilitate the above efforts and provide relevant measures for the improvement of rice production at the field level. At present, many national rice research programmes are well organized and developed. Upstream research deserves more attention from funding donors and scientists in order to increase the rice productivity and production, with more emphasis being placed on rainfed and marginal ecologies to support the world's current population growth. As financial and human resources are limited in many countries, regional/inter-regional and international collaboration and cooperation in rice research would offer practical solutions to meet the world's increased food demands.

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