SUSTAINABLE INTENSIFICATION OF RICE PRODUCTION FOR FOOD SECURITY IN THE NEAR FUTURE – A SUMMARY REPORT

Nguu Van Nguyen
Secretary, International Rice Commission

Rice is the staple food of more than 3,000 million people. Global rice production, however, has become unstable after 1999. The surge in rice prices since 2007 has affected food security in several developing countries where rice is the staple food crop. The rate of growth of rice yield increases is declining, while water and land resources for rice production - especially in Asia - are becoming scarce. The food security of rice consumers depends, therefore, on greater national, regional and international efforts and investments toward achieving sustainable production increases. Policy makers need information on the situation of rice production and on improved technologies that are available for sustainable intensification of rice production in order to formulate appropriate policies for supporting rice production.

EVOLUTION OF GLOBAL RICE PRODUCTION: 1961 TO 2006

Global rice production was only 215 million tones in 1961, after thousands of years from the time when rice cultivation first took place. Within the span of 45 years the global rice production rose to 644 million tonnes in 2006 or an increase of 429 million tonnes. During the first 15 years, 1961 to 1975, global rice production increased by 141 million tonnes or 9.4 million tonnes per year. Increases in both harvested area and yield were responsible for the increase of global rice production from 1961 to 1975. Global rice harvested area increased by 26 million hectares or 1.73 million hectares/year, while world rice yield increased by 0.65 tonnes/ha or only 43 kg/year (Table 1).

In the next 15 years, 1976 to 1990, the global rice production increased rapidly by 171 million tonnes or 11.4 million tonnes per year. During this period, the global rice harvested area, however, increased only 5 million hectares or 0.33 million hectares/year, while the world rice yield increased 1.07 tonnes/ha or 0.071 tonnes/year. Productivity increase, therefore, was the main factor behind the increase of global rice production during this period (Table 1).

The growth in world rice yield, however, had slowed down considerably in the next 16 years, from 3.53 tonnes/ha in 1991 to 4.12 tonnes/ha in 2006 or an increase of 0.039 tonnes/year. The increase in global rice harvested area was substantial about 10 million hectares or 0.55 million hectares/year, but the expansion rate was much lower than that in the first 15 years, from 1961 to 1975 (Table 1)

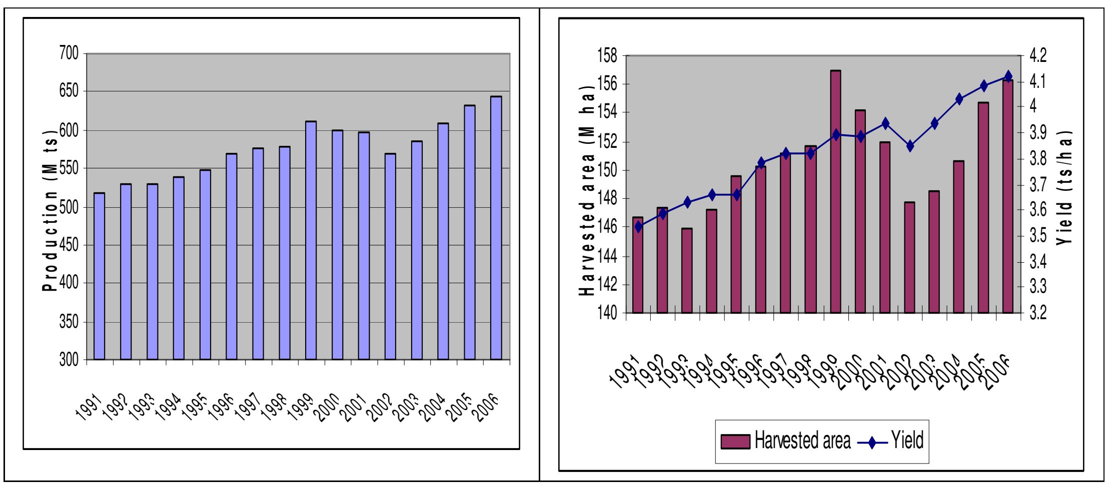
Table 1 Global rice production and rice harvested and the world's average rice yield in selected years.

	Production (million tonnes)	Harvested area (million hectares)	Yield (tonnes/ha)
1961	215	115	1.86
1975	356	141	2.51

Change (1975-1961)	*+ 141*	*+ 26*	*+ 0.65*
1976	347	141	2.45
1990	518	146	3.52
Change (1990-1976)	*+ 171*	*+ 5*	*+ 1.07*
1991	518	146	3.53
2006	644	156	4.12
Change (1991-2006)	*+ 126*	*+ 10*	*+ 0.59*

Although global rice production fluctuated now and then in 1961-1999, the production decreases, however, were often not deep and lasted for only a year to a maximum of two years. For the first time, global rice production decreased sharply and for a rather long period, from 1999 to 2002 (Figure 1). The decrease of global rice production during the period from 1999 to 2002 was caused by a sharp decrease in global rice harvested area. Although global rice production has recovered since 2003, the sharp decrease of global rice production from 1999 to 2002 suggests that the global rice production might become unstable in the future.

Figure 1 Global rice production (left) and global rice harvested area and world's average rice yield (right), 1991-2006



THE DIVERSE RICE ECOSYSTEMS

The environmental and socio-economic conditions of rice production vary greatly from country to country as well as from location to location. The diverse environmental and socio-economic conditions have affected the performance of rice production in the past 45 years. They also influence the opportunities for increasing rice production in the future. Environmentally, rice is grown under different climates including temperate, sub-tropical and tropical. Within a climate the weather varies from arid and semi-arid to sub-humid and humid. Based on soil-water conditions rice production ecosystems include irrigated lowland, irrigated upland, rainfed lowland, rainfed upland and deepwater/floating ecosystems. Socio-economically, farm size cultivated by a household in South Asia, Southeast Asia, East Asia, and Africa is generally small, which varies from less than one hectare to few hectares. The ratio of rice land to arable land is high in South Asia, Southeast Asia, and East Asia (Table 2).

With the exception of Japan and Korea Rep, rice cultivation in South Asia, Southeast Asia, East Asia, and Africa still uses enormous amounts of human labour, in spite of strikes made in mechanization of rice production. On the other hand, farmers in Europe, America and Australia cultivate large farms and rice cultivation is highly mechanized with large expenditures of energy from fossil fuels.

Table 2 Rice production (1000 tonnes) and harvested area (1000 hectares) and arable land (1000 hectares in some selected countries in 2000

	Rice production (1000 ts)	Rice harvested area (1000 ha)	Arable land (1000 ha)	Rice harvested area/Arable land
China	190,668	30,503	124,144	0.245
India	134,150	44,600	161,500	0.276
Indonesia	51,000	11,523	17,941	0.642
Bangladesh	25,521	10,700	7,992	1.338
Viet Nam	32,554	7,655	5,700	1.342
Thailand	23,403	10,048	16,800	0.598
Myanmar	20,125	6,211	9,548	0.650
Philippines	12,415	4,037	5,500	0.734
Japan	11,863	1,770	4,535	0.390
Brazil	11,168	3,672	53,200	0.006
USA	8,669	1,232	176,950	0.069
Korea Rep	7,067	1,072	1,708	0.627
Pakistan	7,000	2,312	21,425	0.107
Egypt	5,997	660	2,834	0.232
Nepal	4,030	1,550	2,898	0.534
Cambodia	3,762	1,873	3,700	0.506
Nigeria	3,277	2,061	28,200	0.073
Iran	2,348	587	16,837	0.034
Madagascar	2,300	1,207	2,565	0.470
Lao PDR	2,155	690	800	0.862
Colombia	2,100	440	2,079	0.211
Malaysia	2,037	692	1,820	0.380
Korea DPR	1,690	535	1,700	0.314
Peru	1,665	300	3,670	0.081
Argentina	1,658	289	25,000	0.011
Ecuador	1,520	380	1574	0.241
Australia	1,400	145	53,775	0.002
Italy	1,300	221	8280	0.026
Uruguay	1,175	185	1,260	0.146
Cote d'Ivoire	1,162	750	2,950	0.254

Irrigated Lowland Rice Ecosystems

In recognition of the important role of water to the productivity of rice crops, efforts have been made to assure adequate water supply to rice cultivation throughout human history through irrigation development. Irrigated lowland rice is grown in bunded fields with assured water supply for one or more crops per year. In temperate and most of the sub-tropical climate areas, rice is grown mostly under irrigated lowland ecosystems, once a year during the warm months; when temperature regimes are suitable for growth and development of rice plants. However, with available irrigation water, rice could be grown more than one crop per year in tropical climate areas. In arid and semi-arid zones of tropical climates, rice is planted under irrigated conditions only, but in humid and sub-humid zones, rainfall supplement irrigation water during the rainy season. In South Asia, Southeast Asia, and East Asia, irrigated lowland rice is dominant in the vast, flat and low-lying flood plains and deltas of many of the world's major rivers, which are flooded annually during the rainy season.

The irrigated lowland rice production systems had benefited from substantial investment during the second half of the 20th century for the building of dams to divert the flow of the river and/or to store surface water and then channel it onto rice fields as well as the drainage systems to convert large part of deepwater and floating rice areas into irrigated rice production. In late 1960s, farmers in a number of countries turned to underground sources and millions of irrigation wells were drilled to provide water to rice production. The irrigated lowland rice systems have benefited much from modern or high-yielding and hybrid rice varieties and associated improved rice technologies. The FAOSTAT Agriculture database counts the harvested area not the area that is planted to rice. Therefore, one hectare of rice land could be counted two or three times if it is planted two or three rice crops in a year. In recent years, the harvested area worldwide from irrigated lowland rice systems was about 88 to 90 million hectares. Because the risk of crop failure is lower than in the other ecosystems, irrigated lowland rice farmers use more production inputs to increase rice yield. The average yields of irrigated lowland rice vary from about 3 tonnes/ha in some countries in Sub-Saharan Africa to 10 tonnes/ha in Egypt.

Irrigated Upland or Aerobic Rice Ecosystems

There were efforts in the 1980s to develop and popularize the irrigated upland rice or aerobic rice production in Brazil using sprinkler irrigation systems. Aerobic rice production was recently practicec in northern China as a response to water shortage. Soils of irrigated upland rice fields are freely drained. The adoption of irrigated upland rice production systems so far has been very limited. It is estimated that the areas planted with aerobic rice varieties was about 80,000 hectares in China and 250,000 hectares in Brazil.

Rainfed Lowland Rice Ecosystems

Rainfed lowland rice ecosystems are found mainly in tropical climate areas; in river deltas, flood plain and inland swamps. Bunds and dikes are built around rainfed lowland fields to capture and conserve rainfall for growth and development of rice plants. Water supply to rice crops comes principally from rainfall, but in some places water may come from diverted small water courses (e.g. streams), or swollen rivers. Rice fields are covered with a layer of standing water up to 50 cm during half of the growing season or more. Variability in rainfall and its distribution normally cause either flood or drought stresses in rainfed lowland rice production.

In Asia the expansion of the irrigated lowland rice area has contributed negatively the total harvested area of rainfed lowland rice, while farmers' efforts to do double cropping in areas with long rainy season have positive contributions. Also, the development of inland valley swamp for rice production in Sub-Saharan Africa contributed to the increase in the harvested area of rainfed lowland rice. In the recent years, worldwide, the harvested area of rainfed lowland rice is estimated to be about 44 to 46 million hectares. Yields of rainfed lowland rice remain low, about 1.5 to 2.5 tonnes/ha in most cases, in spite of series of modern and high yielding varieties that were made available by international and national institutions worldwide.

Rainfed Upland Rice Ecosystems

Rainded upland rice fields are found mainly in tropical climate areas; on flat land or on slopes of hills and mountains. They are normally not surrounded by bunds or dikes. Soils of rainfed upland rice fields are freely drained during most of the growing season. Rainfall is the only source of water supply to rice growth and development. Rice yield and production, therefore, vary considerably from year to year depending on the amount of rainfall and its distribution. Drought stress is a major factor affecting rice yield and production. In spite of series of modern and high yielding varieties that were made available by international and national institutions worldwide yields of rainfed upland rice remain very low about 1.5 tonnes/ha or less in most cases. Harvested area of rainfed upland rice in Brazil decreased significantly since the 1980s, but that in Sub-Saharan Africa increased steadily. In the recent years, the harvested area of rainfed upland rice is estimated to be about 15 to 16 million hectares.

Deepwater/Floating Rice Ecosystems

Deepwater/Floating rice ecosystems are found in low lying areas in deltas, estuaries, swamps, and rivers' valleys in tropical Asia and sub-Saharan Africa, where the water is stagnant for some time during rice growing season. During the early part of the rice growing season, water supply to rice crop comes mainly from rainfall. However, as the cropping season progresses, water from swollen rivers and from high-lying ground inundated rice fields for considerable period of time. Depth of standing water in rice fields during considerable period of the cropping season could be up to 100 centimeter in deepwater rice ecosystems and to more than 1 m and sometimes were up to 6 m in floating rice ecosystems. Most of tidal affected rice area belongs to deepwater rice ecosystems. Varieties planted in deepwater rice ecosystems could elongate 2-3 cm per day when submerged, while those planted in floating rice ecosystems could elongate rapidly sometimes up to 20 cm per day when submerged. Varieties planted in tidal affected rice areas have good tolerance level to salinity. In the past, there were about 11 million hectares of deepwater and floating rice. However, large areas have been converted for irrigated rice production through the development of irrigation and drainage systems. In recent years, it is estimated that the harvested area of deepwater and floating is about 3 to 4 million hectares. Rice production in these ecosystems has not benefited much from research and development in the past. Yields of deepwater/floating rice are about 2 tonnes/ha or less.

ISSUES AND TECHNOLOGICAL OPPORTUNITIES FOR SUSTAINABLE RICE PRODUCTION

Presently, the world's population continues to increase, although at lower growth rates. On the other hand global rice production is confronting issues such as climate change and the scarcity of water, land and energy resources. The issues and opportunities for sustainable increase of rice production differ from one rice ecosystem to another due to differences in environmental and socio-economic conditions, degrees of intensification, especially during the last 45 years, and crop management operations. Fortunately, there are existing improved and promising technologies that could be employed to boost farmers' production and to increase their incomes, while ensuring environmental conservation.

Genetic Improvement

Yield potential of both *japonica* and *indica* rice, especially of irrigated lowland rice, has greatly increased thanks to genetic improvement. Before the Meiji period *japonica* rice yields in Japan were low. The discovery of the variety Shinriki that had a short stem and produced outstanding yield when applied with high rates of fish-based fertilizer had increased rice yield and production. Consequently Shinriki was then used in the development of high-yielding japonica rice varieties in Japan and later in other countries where *japonica* rice is widely cultivated.

Similarly, in tropical climate areas, where *indica* rice is dominant, rice yields on farmers' fields before 1950 rarely exceeded 2.5 tons/ha. In the 1950s the International Rice Commission implemented an international *indica-japonica* hybridization project, which produced and released for cultivation some improved rice varieties such as ADT 27 in Tamil Nadu, India and Mashuri in Malaysia. But yield potential of rice in tropical and subtropical climates substantially increased only after the release of IR8 by the International Rice Research in 1966. Over the years, IR8, which contains the *sd1* gene, has been intensively and extensively used as a parent in rice varietal improvement programmes in many countries. It is estimated that high-yielding semi-dwarf varieties occupy more than 90% of the harvested area from irrigated lowland rice ecosystems. The yield potential of current high-yielding varieties grown in the tropics is around 10 tonnes/ha during the dry season (high radiation) and 6.5 tonnes/ha during the wet season. Since the development of IR8, however, only marginal yield increases have occurred in high-yielding rice varieties. The development of New Plant Type (or Super rice) and C4 rice with higher yield potential is still in progress and has only limited results.

In 1975, in China, the application of the *cytoplasmic male sterile* in wild rice led to the development of hybrid rice and this further increased the rice yield potential by at least 15% or more. The area planted to hybrid rice in China increased practically zero in 1976, to more than 50% of the country's total harvested rice area in 1993. However, Chinese national rice yield has stagnated since 1998, suggesting the limited gains in yield potential of hybrid rice in China.

Before 1990, there was no hybrid rice commercial cultivation in countries outside China. However, the recommendation made by the 17th Session of the International Rice Commission in 1990 in Brazil led to the commercial hybrid rice production in about 1.5 million hectares in 2004 and about 3.5 million hectares in 2008 in countries outside China. The total hybrid rice area, however, still occupies only a very small percentage of the total irrigated lowland rice area in countries outside China and it suggests the potential of hybrid rice for sustainable increase of rice yield and production in irrigated lowland ecosystems in the future.

The wide adoption of high-yielding and hybrid rice has been limited in irrigated lowland ecosystems. In rainfed lowland rice ecosystems, the majority of farmers still do not adopt high-yielding and hybrid rice because of the risks associated with floods and drought. In many low-lying areas where levels of water exceed 30 cm for extended periods or where young rice plants are completely submerged for 10 days or more, farmers tend to revert to growing traditional rice varieties. The International Rice Research Institute incorporated the *Sub 1A* gene into high-yielding varieties has recently developed a number of improved varieties with good tolerance to submergence for rice production in rainfed lowland ecosystems.

Similarly in rainfed upland rice ecosystems most farmers still planted low-yielding traditional rice varieties, which have better drought tolerance and compete better with weeds. Recently the West Africa Rice Development Association (WARDA) or African Rice Center has developed series of NERICA varieties from crosses between *O. sativa* and *O. glaberrima* for production in upland areas of tropical Africa. Under low-input upland ecosystems in West Africa NERICA rice varieties yielded higher than the existing rice varieties.

Minimizing the Effects of the Scarcity of Water, Land, and Labour Resources

Water and land resources for rice production are being threatened by the competing needs of the cultivation of other food, feed and energy crops and the expansion of industrialization, urbanization. In addition, the migration from rural to urban areas in Asia and Africa has decreased substantially the labour resources, especially male labour in agriculture. In addition to the adoption of high-yielding and early maturing rice varieties, the application of combinations of existing technologies would save time, land and water for intensification of rice production in the future:

Minimum and/or zero tillage: The common benefits of conventional land preparation in rice production are weed control, incorporation of fertilizers, increase in soil porosity and aeration, mixing the soil to bring up leached deposits and giving the soil a good condition to increase adsorption of nutrient. However, conventional land preparation consumes time and energy. Moreover, in lowland ecosystems land preparation consumes about 30% of the total amount water used in rice production, while in upland ecosystems it exposes soils to water and wind erosion. The search for substitute function of tillage operations has led to minimum and/or zero tillage practices. The main benefits of minimum and/or zero tillage practices are conservation of organic matter and soil moisture, reduction in water and wind erosion, reduction in fuels and animal and human energy, and time and water required for land preparation, and possible provision of favourable environment for biological activity. The adoption of minimum and zero tillage in rainfed upland rice production in Asia and Sub-Saharan Africa is still limited. Similar observation was true among rainfed irrigated lowland rice farmers. However, the adoption of minimum and zero tillage among rainfed upland rice farmers in Brazil who have the tradition of using large tractors to prepare land has increased in the recent past. The main constraint of the application of minimum or zero tillage in rice production is weed competition. Application of herbicides is currently used to suppress early weed growth in minimum or zero tillage in rice production. The development of alternative weed management approach would contribute to the adoption of minimum or zero tillage in rice production.

Land levelling using laser beam: In rainfed and irrigated lowland rice ecosystems, it is essential to have land levelled for good water management and also for weed control and the efficiency of nitrogen use. Farmers, especially in Asia, have the tradition to do soil puddling for land levelling. However, soil puddling requires substantial water and time. Land levelling using laser beam was developed for land levelling and its adoption is increasing worldwide, thanks to the advance in farm mechanization.

Direct seeding in lowland rice production: Farmers in Asia and Africa have the tradition of transplanting lowland rice. Transplanting uses less seed but requires more labour, time and water. It normally requires about 120 man-hours to transplant a hectare. Direct seeding on dry soils has been used by lowland rice farmers in Asian countries such as Indonesia and Philippines who grow two rice crops within a year in rainfed areas with long rainy season. The system is called *gogo-rancha* in Indonesia and *sabog-tanim* in the Philippines. In USA, irrigated lowland rice farmers use direct seeding on dry soils. Direct seeding onto flooded and saturated soils has been used by farmers in South America and Europe. The adoption of direct seeding onto flooded and saturated soils has increased in Asia due to labour shortage in rural areas. Direct seeding, however, requires large quantities of seed. Also weed competition in direct seeded fields is high.

Rotational and intermittent irrigation: Rice thrives well in both flooded and dry field as long as water supply is assured. Experiments conducted by the International Rice Research Institute in the 1970s show that yields of irrigated lowland rice were highest when fields were maintained at saturated level. In addition, rotational irrigation was found to be the most efficient operation in irrigation systems. Farmers in rainfed lowland rice ecosystems build bunds to store rain water as measure to prevent possible drought caused by erratic rainfall distribution. Also, lowland rice farmers flood rice field as a way to keep down weed competition. Improvement in weed management would promote the adoption of rotational and intermittent irrigation to increase the efficiency of water use in irrigated lowland rice production.

Aerobic rice or irrigated upland rice: Water consumption in aerobic rice ecosystems was lower than that in flooded lowland rice systems. Yields of aerobic rice, however, are still about 80% of that in irrigated lowland rice ecosystems. Moreover, in Brazil yields of aerobic rice decrease substantially in areas where rice was cropped continuously.

Confronting the Declining Soil Fertility, Increased Pressure from Pests and Diseases, and the Degradation and Pollution of Environment

The intensification of rice production has harmed the environment. The excessive use of pesticides causes water pollution and human health hazards. Intensive irrigation with inadequate drainage has increased the salinity level in rice soils in semi-arid and arid zones. After years of high yields, rice soils are depleted of nutrients. The application of combinations of following existing technologies would be necessary for sustainable intensification of rice production in the future:

Soil fertility: In the past, traditional rice farmers in Asia used raw organic matter, human and animal manures, ashes, fish bone and other waste materials to make the rice plant more productive. Compost and green manures had also widely used. Compost was a major factor for farmers to win in yield contests organized in Japan during 1948-1968. In many countries green manure is regarded as an important nutrient source for rice. Azolla for example had been widely used by farmers in China and northern Viet Nam to fertilize rice crops. The use of compost and other organic sources of fertilizer, however, has declined with increased industrialization, high cost of labour, and the availability of inorganic fertilizers.

Site and season specific nutrient management and recommendations could reduce nutrient losses and chemical pollution of the environment. Soil analysis is widely practiced by farmers in developed countries for determination of fertilizer types and doses for application to rice crop. The majority of farmers in developing countries, however, could not afford the cost of soil analysis. Integrated Plant Nutrient Management (IPNM) systems promote the application of balanced doses of inorganic and organic fertilizers and the application of fertilizer doses based on the responses of rice varieties planted in different eco-zones and in different seasons. It has been found that IPNM is more beneficial in maintaining rice soil fertility and it has been widely adopted in irrigated lowland rice production in many countries.

Among the mineral element, rice crop requires considerable amount of nitrogen. In the 1970s and 1980s, the International Rice Research Institute and a good number of national institutions recommended the application of 2/3 N rate before transplanting and 1/3 N rate at panicle initiation stage in order to improve the efficiency of nitrogen fertilizer use in the cultivation of high-yielding varieties. Recently, the use of chlorophyll and leaf colour chart has been recommended for determination of nitrogen requirement of rice plants during their growth.

Pests and diseases: In the 1970s up to the early 1980s the application of large doses of pesticides were recommended in irrigated lowland rice production together with resistant rice varieties. Considerable evidence has been produced to challenge the need for routine chemical treatment to protect the rice crop. Also some rice insects and diseases have different biotypes and races. A resistant variety may become susceptible after being successively cropped for a period of time because the insect develops new biotype. For example IR36, released in 1976, has high level of resistance to brown plant hopper, a major rice insect of rice in Asia that transmit ragged stunt virus. After few years of wide cultivation, IR36 was severely damaged in mid 1980s by a new biotype of brown plant hopper and the associated ragged stunt.

Rice fields harbour a tremendous diversity of animals, plants, and micro-organisms; some of them are harmful, while others are beneficial to rice crop. Integrated Pest Management (IPM), therefore, was popularized for rice production. The basic premise of IPM is that no single pest control can be completely successful and crops may sustain certain degrees of damages before yields are affected. The IPM is an approach to crop protection based on understanding and managing the agro-ecosystem to create conditions that suppress the development of pests and diseases. Important elements are conservation of natural enemy populations for insect pest control. Techniques applied under IPM include a broad variety of agronomic practices to suppress pest and disease development, biological control agents, insect lures and traps and if additional use of pest management inputs is justified, chemical pesticides may be applied to limit the building up of the population of harmful insect or disease.

Weeds limit rice yield greatly in all ecosystems through competition with rice for sunlight, water and nutrients. Weed competition during early growth stages of rice reduces rice yield greatly. Weed management is more difficult in direct seeding than in transplanted rice. Manual weeding requires time and man power, sometimes up to 150 man-days per hectare, especially in upland ecosystems, while herbicide treatment could be costly and may have undesirable effect on the environment of rice field and surrounding areas. In addition some weeds develop resistance to repeated herbicide application. Integrated Weed Management promotes the use of rice varieties with superior weed competitiveness, use clean seed, biological control, allelopathy, cultural practices and herbicide application. Optimum combination of weed management may differ greatly depending on the type of rice culture and resources available to farmers.

Integrated Crop Management to Close the Yield Gap and to Increase Farmer's Income

The availability of information technology and other technologies since the 1980s provides the farmers in developed countries with new tools and approaches to characterize the nature and extent of variation in the fields, enabling them to develop the precision farming system for precisely managing rice crop based on specific conditions, thus increasing the efficiency of input application. Agricultural research and education institutes in developing countries are familiar with the precision farming system. However, the technologies and tools used in precision farming system in developed countries are beyond the reach of resource-poor farmers in developing countries.

The 19th Session of the IRC in 1998 directed special attention to the yield gap in irrigated lowland rice production and noted that bridging the yield gap was the most appropriate means of increasing yield and profitability in the highly productive irrigated lowland rice ecosystems. In September 2000, the Secretariat of the International Rice Commission organized the Expert Consultation on Yield Gap and Productivity Decline in Rice Production. One recommendation of the Consultation was the adoption of a system to help farmers to identify all factors influencing production. Such an integrated approach, referred to as Rice Integrated Crop Management (Rice - ICM) has been extremely successful in closing the gap between potential and actual rice yields. One of such system, developed in Australia in the late 1980s, called RICECHECK helps pinpoint which factors are causing reduced yields so farmer can respond with focused action. After a little more than a decade of using this system, Australian national rice yield jumped from 6 tonnes/ha to over 9.5 tonnes/ha.

Since 2000, FAO, in collaboration with selected member countries in Asia and Latin America, developed and transferred Rice-ICM systems, which are based on the following understanding:

- Rice production limitations are closely interrelated. For example, stronger seedlings from high quality seeds will not benefit yield if the crop is inadequately fertilized; and likewise rice crop cannot respond to fertilizer application if weed infestation is intense and water supply is inadequate.
- Rice crop has distinct developmental phases and at every phase, rice crop should attain certain level of growth in order to be able to produce a (particular) yield. The defective growth during a developmental phase could only be partially remedied with crop management in the next developmental phases.
- Regular field observations on the growth and development of the rice crop during the growing season (Table 3) would help farmers to improve their management skill over time, especially through discussion with other farmers and extension officer at regular meetings during the cropping season. Also, farmers' records on the growth and development of the rice crop during the growing season could help the research to determine new experiment for developing new crop management technologies for the area.

Table 3 Recommended technologies and field observations in the Rice – ICM system for IR64 production during dry season in Java, Indonesia – An example

Recommended technologies	Recommended field observations/activity
Seed and seed rate: Use 25 kg/ha seed with 80 t0 90% germination	Conduct simple germination test
Land preparation: Assure good land levelling	No high or low spot in the field
Crop establishment: Transplant 15 to 21 days-old seedlings at 1 to 2 seedlings/hill and at spacing of 20 cm x 20 cm; replanting dead seedlings or those damaged by golden snails	Count number of tillers at 15 days after transplanting. Optimum number of tiller per square meter = 100 to 120 tillers
Nutrient management: Based on recommendation of extension, research or best farmers in your area to determine types of fertilizer to apply and their doses. Apply ½ N dose, full doses of other fertilizers and organic manures/compost as available basally. Use Leaf Colour Chart for determination of time and nitrogen rate for top-dressing	Count number of tillers and observe leaf colour with Leaf Colour Chart at 30, 45 to 50 and 65 to 70 at days after transplanting. Based on observed leaf colour and number of tiller, determine N rate for top dressing. Optimum number of tillers/panicles per square meter at 30 days = 350 to 400 tillers; at 45 to 50 days = 500 to 600 tillers; at 65 to 70 days = 500 to 600 panicles.
Pest and disease management: Apply Integrated Pest Management principles	Damage should be less than 5% at any time during the cropping season. Report to and seek advices from best farmer or extension officer or researcher for measure to take
Weed management: Use a combination of hand weeding, mechanical weeding with rotary weeders and chemical treatment depending on labour availability and cost of herbicides.	Observe weed population and do weeding as needed. Normally first weeding takes place at 15 days and second weeding takes place at 30 days after transplanting to keep field clean. Follow advice of extension officer or best farmers in selection of herbicides and follow the instructions on the containers of herbicides
Irrigation water management: Saturated soil to 5 cm flood provides best rice growth and development. However, determination of the depth of irrigated water should be based on irrigation schedule of irrigation authority and climate in your area to in order to assure adequate supply of water to rice crop, especially during the period from 40 to 70 days after transplanting. Drain water at about 10 days before the harvest	Observe your crop. Optimum water management should assure no drought stress such as rolling leaf, wilting leaf at all times and especially during the period from 40 to 70 days after transplanting.
Time to harvest: Harvest the rice crop when 95% of grains on the panicle turn straw colour.	Expected yield at 14% moisture content = 8 tonnes/ha or more

The results of the pilot tests on the development and dissemination of Rice – ICM showed that the application of Rice – ICM systems increased yields of existing rice varieties by as much as 1 to 4 tonnes/ha, decreased the use of production inputs such as inorganic fertilizer and pesticides, increased the percentage of milled rice, and finally increased the economic return from rice production. The 21st Session of the International Rice Commission that met in Peru in 2006 recommended the organization of an Expert Consultation to formulate the strategy for scaling up the transfer of Rice – ICM systems.

The System of Rice Intensification

The System of Rice Intensification (SRI) was developed in Madagascar in 1986 and has recently been popularized in other countries in sub-Saharan Africa, Asia and Latin America. SRI recommendations include:

- Transplanting of very young seedlings (8 to 10 days after germination), 1 seedling/hill at wide spacing up to 50 cm x 50 cm,
- Frequent weeding using rotary weeders before canopy closes,
- Application of large amounts of compost or organic fertilizers,
- Draining extra water to keeping rice field at saturated condition, not flooded

Rice yields, which were above 15 tonnes/ha, were frequently reported by the SRI promoters. However, results of field experiments conducted by the International Rice Research Institute and its member countries showed no yield advantage from SRI. An international investigation is necessary to clarify the different results before appropriate strategy could be developed for supporting rice farmers.

OTHER ISSUES RELATED TO SUSTAINABLE RICE PRODUCTION

Climate Changes

Flooded rice is a major source of methane emission, while the use of nitrogen fertilizers produces nitrous oxide; both are greenhouse gases linked to global warming. On the other hand, temperature increase, variability in rainfall and its distribution, and rise in ocean water potentially have important effect on rice production. High atmospheric temperature could reduce rice yield in tropical climate areas, while variability in rainfall and its distribution could lead to more frequent and severe floods and droughts. Rising ocean water could expand substantially rice area influenced by tidal waves in low-lying flood plains and deltas of rivers where rainfed lowland, irrigated lowland and deepwater/floating rice are widely cultivated, especially in East Asia, Southeast Asia and South Asia. In addition to the above mentioned-technologies, generations of new rice varieties would most likely be needed for sustainable rice production under climate change.

Malnutrition in Rice Consuming Populations

Although malnutrition in rice-consuming population is caused by problems associated with socio-economic and developmental factors rather than rice consumption alone, protein-energy malnutrition (PEM), vitamin A deficiency, anaemia due to iron deficiency, iodine disorder (IDD), and zinc deficiency are still found in populations, which consume rice as staple food. Considerable efforts have been given to the development of high-yielding varieties with better nutrition values, especially the content of iron, zinc, and vitamin A in rice grains. It is also expected that improvement in income would lessen the malnutrition in rice-consuming population. For example, *beriberi*, a nutrition problem associated with the deficiencies of thiamine and riboflavin among rice-consuming populations, especially in Asia, has gradually disappeared with increased income that could afford the population to have more varied diets. On the other hand, prices of the high quality rice such as Basmati and Jasmine in the international rice markets are normally high and this encourage farmers to shift away from producing high-yielding rice to producing high-quality rice, although yield potential of high-quality rice is generally low.

Maximizing the Value of Rice Harvests

High yields will only lead to additional production if accompanied by improvements in post-harvest operations. Losses from post-harvest operations range from 10-30 %. Although technologies for post-harvest operations are available, post-harvest handling of rice in much of South Asia, Southeast Asia and Sub-Saharan Africa is still not substantially improved due to poverty, lack of credit, and absence of efficient systems for supply and repair of equipment and implements for post-harvest handling of rice. About 60 % of output from rice production is in the form of straw and husk. The burning of rice straw and husks has caused air pollution and contributed to global warming. Although they are not consumable as food, rice straw and husk are good sources of energy and could be used as feed to ruminants. Reduction of post-harvest losses and conversion of rice straw and husks to value-added products could increase farmers' income and reduce environmental pollution.

Rice Biotechnology

Biotechnology holds the potential for increasing yield, reducing inputs and environmental pollution, and meeting the challenges from climate change. For instance, biotechnology could one day create drought resistant variety or a variety that could fix nitrogen in the air. *Bt* rice, herbicide-resistant rice, and golden rice with high level of vitamin A in grains, for example, have been successful in trials. Adoption of the transgenic rice, however, needs still to overcome the concern on human and environmental safety and the question of who would reap the benefits – will farmers benefit along with multinational companies reap the benefits?

Policy and Institutional Environment

The majority of rice farmers are poor and caught in the endless cycle of poverty and food deficit, but national policies in countries, where rice is the staple food crop, usually favour the rice consumers, not the farmers; by limiting the prices of rice in the market. With the increase in prices of inputs and low rice prices, rice production does not provide farmers with high income. Rice food security needs clear national policy that allows right investment in all phases of rice development. There must be right policies on input availability, output marketing and prices. Furthermore, investment in rural infrastructure such as road, irrigation, communication and credit must match the growing demand for rice production.

The rice Green Revolution in the 1970s and 1980s was possible thanks to the investment in research and extension services to build capacity and expertise in rice production. The success of rice Green Revolution has led to reduction in public investment in rice research and extension in general. Policy must be readjusted to provide more support to the development and transfer improved technologies for sustainable rice production.

CONCLUDING REMARKS

As the 21st century unfolds, global rice production has showed signs that it may no longer be stable in the future. On the other hand the global population continues to increase, although with lower growth rate, while the resources for rice production are diminishing. There are many constraints and challenges to reduce rice food shortage, lessening rural hunger and poverty within the rice-based systems. Fortunately, there are technical opportunities to address the constraints and challenges. Rice is the staple food crop of more than half of the world population. It is hoped that the above information and analysis would contribute to the formulation of appropriate policy and strategy for the promotion of sustainable rice production intensification.