IRRI DISCUSSION PAPER SERIES NO. 31

China and IRRI: Improving China's rice productivity in the 21st century

Proceedings of the China-IRRI Dialogue held in
Beijing, People's Republic of China
7-8 November 1997

G.L. Denning and T.W. Mew, editors

IRRI
International Rice Research Institute

Chinese Academy of Agricultural Sciences

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 16 nonprofit international research centers supported by the Consultative Group on International Agricultural Research (CGIAR). The CGIAR is sponsored by the Food and Agriculture Organization of the United Nations, the International Bank for Reconstruction and Development (World Bank), the United Nations Development Programme (UNDP), and the United Nations Environment Programme (UNEP). Its membership comprises donor countries, international and regional organizations, and private foundations.

As listed in its most recent Corporate Report, IRRI receives support, through the CGIAR, from a number of donors including UNDP, World Bank, European Union, Asian Development Bank, Rockefeller Foundation, and the international aid agencies of the following governments: Australia, Belgium, Canada, People's Republic of China, Denmark, France, Germany, India, Indonesia, Japan, Republic of Korea, The Netherlands, Norway, Philippines, Spain, Sweden, Switzerland, Thailand, United Kingdom, and United States.

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

IRRI Discussion Paper Series

The IRRI Discussion Paper Series was created as a flexible means for IRRI scientists to share information with specialized institutions and individuals. Each paper is produced from camera-ready copy supplied by the author and is processed through IRRI's Communication and Publications Services.

The series is intended to be a fast means of presenting preliminary results of research still in progress, but which could be of immediate use to others. The series also contains special project reports, consortia and network reports, short proceedings or reports of meetings and workshops, recommendations from a particular workshop, and similar materials.

IRRI invites feedback from readers, which will be useful to the authors when they are refining their materials for formal publication in journals or as monographs.

MCPO Box 3127, 1271 Makati City, Philippines
Phone: (63-2) 845-0563,812-7686
Fax: (63-2) 891-1292, 845-0606
Email: IRRI@CGIAR.ORG
Home page: http://www.cgiar.org/irri
Riceweb: http://www.riceweb.org
Riceworld: http://www.riceworld.org
Telex: (ITT) 40890 RICE PM
(CWI) 14519 IRILB PS
(RCA) 22456 IRI PH
(CWI) 14861 IRI PS

Suggested citation:
Denning GL, Mew TW, editors. 1998. China and IRRI: Improving China's rice productivity in the 21st century. Manila (Philippines): International Rice Research Institute. 104 p.

ISBN 971-22-0123-6
ISSN 0117-8180

IRRI DISCUSSION PAPER SERIES NO. 31

China and IRRI: Improving China's rice productivity in the 21st century

Proceedings of the China-IRRI Dialogue held in
Beijing, People's Republic of China
7-8 November 1997

G.L. Denning and T.W. Mew, editors

1998
IRRI
INTERNATIONAL RICE RESEARCH INSTITUTE

Chinese Academy of Agricultural Sciences

Contents

Welcome and opening remarks

Lu Feijie
President, Chinese Academy of Agricultural Sciences (CMS)

Respected Experts, Guests,
Ladies, and Gentlemen:

Today, I solemnly open the China-IRRI Cooperation and Exchange Meeting jointly sponsored by the International Rice Research Institute and Chinese Academy of Agricultural Sciences in Beijing. On behalf of CAAS I extend our warm congratulations to the meeting participants and also a warm welcome to Dr. G.H.L. Rothschild, Director General of IRRI, and all experts and guests from both here and abroad.

China is a huge country with a huge rice production. Its rice area is about 31 million ha. In 1996, the total rice yield reached 195 million t, which accounted for 38% of the total grain production of the country. Nearly 60% of the population eats rice as a staple food. Science and technology have played a very important role in rice production. The breeding for dwarf stem rice, the improvement of cropping systems, and the release of hybrid rice have dramatically improved rice production per unit area as well as total production.

Since the implementation of reformation and the open door policy, we have made changes in the rural economic system, which greatly helped improve productivity and promoted the development of agricultural production. The application of new techniques including biotechnology for improving the yield and quality of rice has attracted worldwide attention. Rice production has guaranteed the fundamental grain supply of the Chinese people, thus ensuring the realization of a total grain production target of 500 million t by the end of this century. By the year 2010, rice yield will reach 570 million t. Producing this is a very arduous task. Therefore, it is important to strengthen agricultural scientific research, to extend advanced technology, and to continuously improve total rice yield as well as rice yield per unit area. Rice is a staple food in many countries in the world so it is no wonder that developments in rice science and technology arouse concern and attention in the worldwide community.

China has already established a bilateral relationship of mutual benefit with IRRI. In the last 20 years, CAAS, various provincial academies of agricultural sciences, and agricultural universities and colleges have successfully collaborated on genetic breeding, biotechnology, integrated pest control, crop cultivation, grain processing, and biodiversity. All these activities not only promoted rice production in China, but also contributed to world rice development. In particular, we are very pleased with our cooperation in resource development and environmental protection while dealing with rice production research. In this meeting, over 60 foreign and Chinese scientists are gathered together to review the progress and achievements of past cooperation as well as the existing problems. We will also discuss areas and mechanisms for future cooperation. I am fully convinced that the scientific research cooperation between China and IRRI will enter a new phase after this meeting.

I wish this meeting a great success!

May all our experts and guests have a very pleasant stay in China!

Thank you for your attention.

Keynote address

Li Xiaofen
Deputy Director, International Cooperation Department, Ministry of Agriculture, China

Distinguished Guests,
Ladies, and Gentlemen:

I am very happy to be here with you today. First of all, please allow me, on behalf of the Ministry of Agriculture, to express our heartfelt thanks for the preparation done by IRRI and the CAAS for this meeting. I would also like to extend a warm welcome to all representatives here today.

China is a large agricultural and huge rice-producing country. Therefore, the Chinese government puts great emphasis on rice research and rice production. China's investment in rice research accounts for a high percentage of the total research budget for grain crops in the Eighth and Ninth Five-Year Plan periods.

The fundamental requirements for developing rice production include: first, reliance on correct policy, second on science and technology, and third on adequate investment. Among these, science and technology are the most important factors behind essential changes in rice production.

International cooperation and exchange are important parts of improving rice production. IRRI is one of the centers of the CGIAR system which entered very early into a formal cooperative agreement with China. During the past almost 20 years, both sides benefited from the exchange of germplasm resources, breeding efforts, integrated pest management, biotechnology, utilization of hybrid vigor, and personnel training. Twenty-five rice varieties have been bred by Chinese scientists through breeding materials provided by IRRI. At the same time, Chinese scientists took an active part in all research networks organized by IRRI. Over 30 Chinese research institutions have joined these networks. Due to the outstanding cooperation between IRRI and China in rice research, the second Director General of IRRI, Dr. N.C. Brady, was awarded the International Agriculture Cooperation Reward by the Ministry of Agriculture of P.R. China.

CAAS is entrusted by the Ministry of Agriculture to coordinate cooperative research and has played a very important role in promoting cooperation on multidisciplines as well as at different levels between IRRI and China. There are over 60 foreign and Chinese scientists attending this meeting. We shall review the achievements gained from our past cooperation and discuss existing problems and areas and opportunities for future cooperation. I am sure that the cooperation between IRRI and China will reach a new level after this meeting.

I sincerely wish this meeting success!

May all the guests have a very pleasant stay in Beijing!

Achievements and prospects of collaborative research between China and IRRI

Cunshan Ying
China National Rice Research Institute, Hangzhou 310006, P.R. China

China is one of the countries in Asia where cultivated rice *(Oryza sativa)* originated. Rice is the staple food in China and is an important element in its history and culture. The Chinese farm is the largest rice area in the world. In 1995, 30.7 million ha were planted to rice, producing a total of 185.2 million t of unmilled rice; the national average rice yield was 6.0 t ha”.

As the main producer and consumer of rice, China is an important partner in IRRI’s efforts to improve the well-being of present and future generations of rice farmers and consumers, particularly those with low incomes. Since IRRI was founded in 1960, Chinese scientists have had many important roles in promoting international cooperation in rice research.

Background and early collaboration

In the early 1970s, a Chinese delegation to the Food and Agriculture Organization (FAO) Regional Conference in Manila paid a courtesy call on the Philippine president who presented the delegation with rice seeds developed at IRRI. This paved the way for formal scientific collaboration with China.

In 1976, Dr. Nyle C. Brady, IRRI director general, led a team of scientists to begin working with the Chinese. Formal planning of collaborative research and training with China began in 1982. The lead agency was the Chinese Academy of Agricultural Sciences (CAAS). IRRI subsequently signed other memorandums of understanding with the Chinese Academy of Agricultural Mechanization Sciences (CAAMS); Academia Sinica; Zhejiang Agricultural University; National Azolla Research Center, Fujian Academy of Agricultural Sciences (FAAS); Rural Development Center of the State Council; and the National Laboratory for Plant Genetic Engineering, Beijing University. IRRI has played a significant role in the planning and establishment of the China National Rice Research Institute (CNRRI).

The research collaboration between China and IRRI was fruitful from the start. One of the first activities was the shuttle breeding program of CNRRI and IRRI between 1983 and 1987. This led to the release of new varieties, Zhongyou I and a series of promising lines.

China established itself as a leader in hybrid rice research when it hosted the First International Hybrid Rice Symposium in Changsha, Hunan Province, in October 1986, a meeting attended by 120 scientists including 60 Chinese nationals. A year later, CNRRI, CAAS, and IRRI jointly sponsored the International Rice Research Conference in Hangzhou. It was attended by 103 participants from 27 countries and international organizations, including 78 Chinese scientists. In 1989, CAAMS and IRRI sponsored a seminar-workshop on “Appropriate Technology for Rural Women” that was funded by the International Development Research Centre (Canada), the Danish International Development Agency, and the Ford Foundation. IRRI conducted training courses on azolla and hybrid rice in Fujian and Hunan at the request of Chinese agricultural institutions.

Collaborative research achievements

The International Network on Soil Fertility and Sustainable Rice Farming (INSURF)

The National Azolla Research Center, FAAS and IRRI through the International Network on Soil Fertility and Sustainable Rice Farming conducted research on genetic improvement and the use of biofertilizer azolla in China. Work on azolla sexual hybridization, mutation, and sporulation was conducted. A new azolla strain, 088, grows fast, produces a high biomass, and has good tolerance for salinity. New strains of azolla, Backcrossing No.3 and Rongping, selected through sexual hybridization, were also saline-tolerant.

INSURF, which was completed in December 1993, introduced a new cropping method based on the rice-azolla-fish system. The system, adopted in more than 100 ha in Fujian Province in 1992, has yields from 13.3 to 14.7 t ha^{-1} a year. Average fish yield was from 7 to 12 t ha^{-1} a year. The new cropping system increased incomes by as much as US$1071-2143 ha^{-1}, decreased chemical fertilizer use by 50-60%, and lessened pesticide application by 30-40%.

The organic matter content in the new cropping system increased from 3.2 to 5.6% whereas the organic matter in traditional paddy fields increased by 4.5%. Azolla also enriches the soil with potassium. After several years of continuous cropping, the rice-azolla-fish culture improved soil fertility, total nitrogen and phosphorus, and available potassium. Soil fertility increased rapidly due to fast accumulation of azolla residue and fish excreta.

In general, the China-IRRI collaboration through INSURF on the use of azolla resulted in a higher grain yield and improved soil fertility, thereby increasing farmers' income and decreasing pollution.

Studies to increase the productivity of rice-azolla-fish culture are also being undertaken in China and other sites in Indonesia, Philippines, and Vietnam.

CAAS continues to conduct research to determine if the fertility of rice soils changes under intensive cropping and continuous application of chemical fertilizers. It is evaluating the effectiveness of various combinations of chemical fertilizers, azolla, green manure, and farmyard manure as nutrient inputs in rice production.

Varietal improvement

Since China and IRRI started collaboration, 19 IRRI breeding lines have been released as farmer varieties in several Chinese provinces (Table 1).

Table 1. IRRI breeding lines named as varieties in China.

Breeding line	Variety name	Province in which released
IR8-288-3	IR8	Guangxi, Guangdong, Fujian
IR661-1-140-3-2	IR24	Guangdong, Guangxi, Fujian
IR1541-102-7	IR26	Jiangsu, Hubei, Anhui
IR1561-228-3	32 Xuan 5	Hunan
IR2061-214-3-8-2	IR28	Hunan
IR2061-464-2-4-5	IR2061	Hunan
IR2071-625-1-252	IR36	Guangxi, Hunan, Anhui
IR15853-89-7	N90	Guangxi
IR19965-48-2	Waiying	Guangdong
IR21015-80-3-3-1-	N304	Guangxi
IR21929-102-2	Mingkang 108	Fujian
IR9129-102-2	Guoji Youzhan	Guangdong
IR19274-26-2-3-1-	Xiang Wanxian	Hunan
IR2061	Minnuo 580	Fujian
IR72	IR72	Guangdong, Fujian, Hunan
IR9965-48-2	Waixuan 35	Guangdong
IR2190-12-3-3	Minkang 108	Fujian
IR19274-28-2-2-1	86-70	Hunan
IR29	HA Nuo 15	Hunan

Hybrid rice

In the late 1970s, China was the first to successfully produce hybrid rice for temperate climate agriculture. This hybrid yields 10% more than conventional rice. China and IRRI conducted basic research on hybrid rice during their first decade of collaboration, and developed promising cytoplasmic male-sterile lines and seed production technology for the tropics. The first Chinese hybrid rices released — Shanyou 2 and Welyou 6 — had IR24 and W6, respectively, as restorer parents. Research collaboration continues among CNRRI, IRRI, Hunan Hybrid Rice Research Center, and the Guangxi AAS.

Germplasm conservation and exchange

From 1990 to 1993, Chinese scientists sent 1137 native rice varieties to IRRI's Germplasm Resources Center. In the same period, IRRI sent China 3124 samples of cultivated races and 1041 samples of wild rice. IRRI collaborates with many institutes in China for the collection and conservation of rice germplasm, including the Institute of Crop Germplasm Resources, CNRRI, the Guangdong AAS, and the Guangxi AAS.

Germplasm evaluation

Chinese breeders exchange and evaluate promising rice lines through the International Network for the Genetic Evaluation of Rice (INGER). China introduced 47,000 accessions including duplicates from INGER, which were applied in 12 testing nurseries for evaluation. Main nurseries are the irrigated rice observation nursery, hybrid rice nursery, blast resistance nursery, and brown planthopper resistance nursery. There are 13 INGER test sites in 11 provinces in China.

Evaluation and utilization of super rice

CNRRI introduced 89 accessions of super rice germplasm from IRRI, and conducts research on their genetic characteristics and yield potential in China.

Biological control of rice pests

Chinese scientists from the Guangdong AAS are looking for useful bacteria that produce high levels of chitinase. Such bacteria are known to inhibit fungi that cause rice diseases.

Researchers at the Jiangsu Academy of Agricultural Sciences (JAAS) are working to isolate nonpathogenic bacteria that suppress seedborne fungal pathogens.

Rice and global climate change

CAAS is looking at how high temperature affects rice pests and their natural enemies, especially the efficiency of natural predators against pests.

Methane, a greenhouse gas that stores 30 times as much heat as carbon dioxide, is produced in flooded soils such as those used for irrigated rice. Scientists from CNRRI and the Institute of Crop Breeding and Cultivation of CAAS are taking part in an IRRI-led effort to compile a database of methane emission level in irrigated rice fields.

As ozone in the atmosphere is destroyed by chlorofluorocarbons, more ultraviolet radiation reaches the earth's surface. Ultraviolet-B (UV-B) radiation can cause damage to plant tissue. Dr. Qiujie Dai, a plant physiologist from JAAS, has been posted at IRRI since 1990 to study the effects of increased UV-B radiation on the rice plant.

Rice-based farming systems research

IRRI is working with 6 national and 10 provincial research institutes on various rice-based farming systems. Dry seeding technology and plastic film mulches were evaluated and are being introduced to farmers in Liaoning. Crop-animal farming systems are also being tested in Beijing, Shanghai, and Jiangsu.

Crop modeling

Three Chinese institutes are participating in the Simulation and Systems Analysis for Rice Production (SARP) network. Using simulation models, Chinese scientists can predict the effects on rice production of pest and disease attacks, nutrient availability, cropping patterns, cultural practices, and environmental conditions. CNRRI and SARP, in particular, have been evaluating the impact of global climate change on rice production in China.

Agricultural mechanization

Chinese agricultural engineers from CAAMS regularly go to Los Baños for training or to do collaborative research with IRRI engineers. IRRI mechanical seeders were adapted for multirow tractor application by researchers at the JAAS.

CNRRI evaluates IRRI-designed machinery to determine its suitability to local conditions.

Molecular breeding

IRRI and Chinese scientists are using molecular markers to locate genes for blast and gall midge resistance. Genes for controlling rice yield components are also being identified. Mapped genes are being incorporated into elite breeding lines to enhance resistance to rice blast. Collaborating institutions in China include CAAS, Guangdong AAS, and CNRRI.

Training

Training and visits of Chinese scientists have been an important component of the China-IRRI collaboration. Since 1978,601 Chinese scientists have participated in IRRI training programs (Table 2).

Table 2. Chinese participants in IRRI's training programs (1978-94).

Participants	Number
Research fellows	15
Special research fellows	12
PhD degree scholars	24
MS degree scholars	46
Nondegredon-the-job training	81
Short-term group training	423
Total	601

Prospects of cooperation between China and IRRI

The collaborative research between China and IRRI has promoted the development of rice research work and rice production in China. To increase rice per unit yield and production (Table 3), China expects extensive collaborative research and exchanges with IRRI on the following aspects:

1. Strengthening exchange, evaluation, and research of rice germplasm resources, and developing novel germplasm and breeding materials resistant to diseases, pests, and weeds by means of a combination of biotechnology and conventional techniques.
2. Breeding of super high-yielding rice, including normal varieties and hybrid rices, and developing novel CMS lines and restorer lines with strong compatibility.
3. Breeding for resistant transgenic rices and molecular marker-aided breeding.
4. Study on cultivating techniques for raising yield potential in both low/middle-yielding and high-yielding paddy fields.
5. Research on the connections between rice and environments including biodiversity change in paddies, influences of pesticides and fertilizers on environments, and countermeasures.
6. Biocontrol and integrated management of the main diseases, pests, and weeds in rice fields.
7. Study on increasing utilization of irrigation water and fertilizer.
8. Study on the influence of global climatic change on future rice production and its countermeasures.
9. Information exchange and its application in rice research and production.
10. Strengthening staff training and personnel exchange.

Table 3. Population and demand for food and rice grain in China (1949-2030).

Year	Population (100 million)	Food: Total demand (million t)	Food: Per capita consumption (kg year^{-1})	Rice grain: Total demand (million t)	Rice grain: Per capita consumption (kg year^{-1})
1949	5	113	210	49	90
1995	12	466	386	183	153
2000	13	500	385	200	154
2010	14	550	390	220	157
2030	16	640	400	250	163

Actual data in 1949 and 1995; predicted data in 2000,2010. and 2030; total demand: rice grain = 40% food.

Breeding strategies for superior high-yielding rice in China

Shaokai Min and Shihua Cheng
China National Rice Research Institute, Hangzhou, 310006, China

Rice is the main staple food in China, contributing nearly 40% to total calorie intake. The performance of the rice sector in terms of production and yield had been very impressive in most of the last four decades. However, rice production and yield have stagnated since 1990 (Table 1).

The wide adoption of semidwarf varieties and hybrid rice led to two breakthroughs in the yield frontier, but implied that further increases in rice yield will be more difficult. Hence, a special collaborative research project on breeding of super high-yielding rice was established by the Ministry of Agriculture in 1990 and extended in early 1997.

This paper presents the breeding targets, strategies, and achievements of the project.

Breeding target

The future demand for rice and yield can be estimated based on the per capita rice consumption of 150 kg and rice cropping area of 31.6 million ha (Table 2).

Besides good quality and resistance to pests, other targets, including yield of superior high-yielding rice under favorable conditions, are expected to meet future requirements (Table 3).

Table 1. Rice planting area, production, and yield in China (1990-95).

Year	Area (M ha)	Production (M t)	Yield (t ha^{-1})
1990	33.1	191.7	5.8
1991	32.6	187.3	5.7
1992	32.1	186.2	5.8
1993	30.4	177.7	5.8
1994	30.2	175.9	5.8
1995	30.7	185.2	6.0

Breeding strategies and breeding achievements

Conventional rice and hybrid rice cover about 50% each of total rice area in China. The conventional rice varieties with superior high yield could be used as parents of hybrid rice. Thus, breeding for both conventional rice and hybrid rice should be undertaken.

Improvement of plant type is a key factor in the success of breeding for superior high-yielding rice. However, developing a new plant type should depend on the various rice ecosystems. In the northeast region of China, the Rice Research Laboratory of Shenyang Agricultural University designed a plant type “with erect large panicle” for japonica rice. A newly developed line, Shennong 265, can reach about 300 panicles m^{-2} with near 4-g weight per panicle. In the south region, the Rice Research Institute of Guangdong Academy of Agricultural Sciences conceived the “early tillering, rapid growth” plant type for indica rice. The yields of such types of varieties as Teqing, Shengyou, and Shengtai have increased by 10- 15% compared with the check.

Recently, the “intersubspecific heavy panicle hybrid rice” was developed by the Rice Research Institute of Sichuan Agricultural University, with 12-18 hills m^{-2} and 225 panicles m^{-2}; the panicle weight of this hybrid rice can reach 5 g, and yield can be 10-15% over that of the leading hybrid rice, Shanyou 63. In the China National Rice Research Institute (CNRRI), a hybrid rice, Xieyou 9308, displayed a compact plant type with large panicle, resistance to lodging, and high yield potential of 11.2 t ha^{-1}.

Table 2. Projected rice production and yield in China.

Year	Production		Yield per unit	
	Quantity (M t)	% increase.	Quantity (t ha^{-1})	% increase'
2000	195.0	6.8	6.2	4.4
201 0	201.0	19.2	6.9	16.3
2030	247.5	35.6	7.8	32.6

'Increasing %in comparison with 1995.

Table 3. Expected yield target of different superior high-yielding rice.

Year	Conventional rice (t ha^{-1})[a]				Hybrid rice (t ha^{-1})[a]			%
	EI(Y)	E&LI(S)	SJ(Y)	SJN	W)	SI&J	LI	increase[b]
1990	6.8	7.5	7.5	8.2	7.5	8.2	7.5	0
2000	9.0	9.8	9.8	10.5	9.8	10.5	9.8	15
2005	10.5	11.2	11.2	12.0	11.2	12.0	11.2	30

[a] Performance at two sites, 6.7 ha $site^{-1}$. successive 2 years.
[b] Yield trial in multiple sites, in comparison with check.

EI(Y) = early-season indica rice (middle and lower reaches of Yangtze River)
E&LI(S) = early- or late-season indica rice (south China)
SJ(Y) = single japonica rice (middle and lower reaches of Yangtze River)
SJ(N) = single japonica rice (north China)
SI&J = single indica or japonica rice
LI = late-season indica rice

Some superior high-yielding rice breeding lines have been developed by enlarging the genetic distance between the male and female parents in conventional rice and hybrid rice breeding projects. Through introgressing japonica into indica rice, some conventional superior high-yielding elite indica lines and restorer lines and cytoplasmic male-sterile (CMS) lines for hybrid rice were improved by CNRRI and other institutions. For example, the indica restorer line 9308 with about 25% japonica and 75% indica genetic background and T2070, and Zhong 419 with tropical japonica background have good combining ability with CMS line Xieqingzao A and I1-32A, respectively. Their hybrids—Xieyou 9308 and Ilyou 2070, and Ilyou 419yielded—10-15% more than the check hybrid Shanyou 63.

Some exotic rice resources such as American japonica were successfully used in the development of superior high-yielding indica rice. For instance, conventional rice line H96-195 and restorer line Chenghui 210 were progenies of the cross between Chinese indica rice line 80-66 and American rice variety Starbonnet, and between Chinese indica restorer line 871028 and American rice variety Lemont, respectively. The two lines have high photosynthetic efficiency. In farmers' paddy fields (0.1 ha) conventional rice line H96-195 and hybrid rice Yayou 210 (Gang 46NChenghui 210) yielded 9.4 and 9.6 t ha^{-1}, respectively, in 1997. In addition, 064A, a CMS line which is a progeny of the cross between Chinese indica and tropical japonica-like rice and has wide compatibility has been used in breeding for superior high-yielding hybrid rice.

Future outlook

Great achievements in breeding for high-yielding rice have been made in recent years.

The yield of some newly bred conventional varieties and hybrid rice varieties is close to the breeding target for superior high-yielding rice. However, it seems that a further increase in yield is more difficult to attain.

The root system is the foundation of the plant. However, the proportion of research effort devoted to the root system has been much less than that allotted to the rest of the plant. For our superior high-yielding rice research project, the root system vigor at various growth stages, particularly during grain-filling, will be comprehensively considered.

Exploitation of the indica/japonica heterosis could heighten yield level. With the development of molecular marker technology (viz., rapid fragment length polymorphism,

[RFLP] and polymerase chain reaction [PCR], etc.) in rice, the subspecies classification of parents can be detected and the suitable contribution of indica and japonica backgrounds in hybrids can be determined for high yield in combination with suitable plant type. On the other hand, the availability of high-density genetic linkage maps now makes it possible to identify and study the effects of the individual loci underlying quantitatively inherited traits (QTLs). Before, it was assumed that complex traits were determined by a large number of genes with relatively small and equal effect. QTL analysis has revealed that the effects of different loci may vary greatly. The molecular marker-assisted selection technique has provided an approach to pyramiding beneficial alleles of QTLs for improving yield and other traits important to humans.

Finally, further collaboration between local institutions and IRRI is expected to accelerate breeding for superior high-yielding rice.

Hybrid rice breeding for super high yield

Longping Yuan

China National Hybrid Rice Research and Development Center, Changsha 410125, China

The concept of super high-yielding rice

What is the yield level of "super high-yielding rice"? It seems that there is no identical answer to this question. Several breeding programs for super high-yielding rice have been proposed since the 1980s.

The first breeding program for super high-yielding rice began in Japan in 1980. The aim of the program was to develop new varieties with 50% more yield than the old varieties within 15 years, i.e., increasing the yield of brown rice from 5.0-6.5 t ha^{-1} in 1980 to 7.5-9.8 t ha^{-1} (equivalent to 9.4-12.2 t ha^{-1} of paddy rice) in 1995.

In 1989, IRRI started the "super rice" program which is now called the new plant type (NPT) breeding program. The goal of this program is to develop a super rice with a yield advantage of 20-25% over the present pure line varieties. The yield potential of a super rice with a growth duration of 120 days is 12 t ha^{-1}.

In 1996, the Ministry of Agriculture in China established a high-yielding rice program with the targets listed in Table 1.

Of course the yield standard in a super high-yielding program should be adjusted based on time, ecological area, and planting season when varieties will be used. However, using the daily yield per unit area as a criterion for super high-yielding breeding programs is more reasonable. Absolute yield as the standard in a superhigh-yielding rice program is not very useful because grain yield is closely related to growth duration.

Based on the present situation of hybrid rice production and the progress of hybrid rice breeding in China, 100 kg ha^{-1} day^{-1} is proposed as the yield goal for breeding super high-yielding hybrid rice by the year 2000.

Morphological model of super high-yielding rice

Good plant morphology is the basis for super high yield, Since Donald proposed the concept of ideotype, many breeders have paid great attention to this important topic and proposed several models for super high-yielding rice, such as the low tillering capacity and large panicle model proposed by Khush, the bushy type and rapid growing model by Huang, the ideal plant type and huge rice model by Yang, and the heavy panicle model by Zhou. These models are good references in current breeding programs for super high-yielding rice since they are all designed based on certain theories and practical experiences.

Table 1. Yield standard of the super rice in China [a].

Phase	Conventional rice				Hybrid rice			
	Early season indica	Any season indica	Single season japonica	Northern China japonica	Early season indica	Single season rice	Late season indica	Yield increase
Present level	6.8	7.5	7.5	8.2	7.5	8.2	7.5	0
1996-2000	9.0	9.8	9.8	10.5	9.8	10.5	9.8	over 15%
2001-2005	10.5	11.2	11.2	12.0	11.2	12.0	11.2	over 30%

[a] t ha^{-1} for two sites of an ecological area with a planting scale of 6.7 ha in each site in 2 consecutive years.

In recent years, a cooperative research program on hybrid rice breeding was conducted by the Jiangsu Academy of Agricultural Sciences and China National Hybrid Rice R and D Center. In this program, the TGMS line Pei'ai 64S was used as the female parent and test crossed with many breeding lines. From these test crosses, several combinations with super high yield potential were screened. For example, the yield trial of Pei'ai 64S/E32 was conducted on a total area of 0.24 ha at three locations in 1997, where the average yield was as high as 13.3 t ha^{-1} and the growth duration was 130 days. This hybrid combination has reached the standard of super high-yielding rice in a small area yield trial.

In recent studies and analysis of hybrid Pei'ai 64S/E32, we found that the most important morphological feature of the super high-yielding rice was the three uppermost leaves which 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; narrow and V-type leaves occupy a relatively small space and therefore accommodate a higher effective LAI; thick leaves have higher photosynthetic function and are not easily senescent. These morphological features mean that a huge source of assimilates is necessary for super high yield.

Large sink and huge source are the prerequisites for super high yield. However, many rice breeders including the author have paid more attention to the sink than to the source. Usually, we are interested in getting breeding materials with relatively high panicle number, big panicles, and desirable 1000-grain weight, resulting in a very large sink but without enough source and therefore undesirable yield.

The following is an analysis of two hybrid combinations, both of which have large sink but different grain yields.

Pei'ai 64S/E32: 2.6 million panicles ha^{-1}; 260 spikelets panicle^{-1} and 88% seed-set; 1000-grain weight of 23.5 g; theoretical yield of 14.0 t ha^{-1} and actual yield of 13.0 t ha^{-1}.

29S/510: 2.7 million panicles ha^{-1}; 236.7 spikelets panicle^{-1} with 90% spikelets fertilized; 1000-grain weight of 25.0 g; theoretical yield as high as 14.2 t ha^{-1} if all fertilized spikelets are fully filled, but actual yield of only 7.4 t ha^{-1}.

The source situation of the two combinations was further investigated. In Pei'ai 64S/E32, the average leaf area and leaf length of the three uppermost leaves was 75 cm^2 and 53 cm, respectively, whereas in 29S/510, it was 41 cm^2 and 39 cm, respectively. The three uppermost leaves of 293/510 were relatively small and thin, and the second leaf was somewhat droopy; therefore, the assimilates produced by the leaves could not fill the sink, resulting in a high rate (35%) of unfilled grains and undesirable actual yield. It is thus clear that the key in breeding super high-yielding rice is to get a huge source base on the present large sink situation.

Based on the characteristics of Pei'ai 64S/E32 and our experiences in hybrid rice breeding, we proposed the following morphological model of a super high-yielding rice (with a growth duration of 130 days):

1. Plant height is about 100 cm with culm length of 70 cm.
2. The three uppermost leaves are
   - long: the flag leaf is 50 cm long and 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 position of the panicle.
   - erect: the leaf angles of the flag, second, and third leaves are 5, 10, and 20 degrees, respectively, with the leaves staying erect until maturity.
   - narrow and V-type: the leaves look narrow but still have a width of 2 cm.
   - thick: the dry weight of the three uppermost leaves in Pei'ai 64S/E32 is 0.98 g 100 cm^{-2}, whereas that of 312S/Guiyunzan is 0.73 g 100 cm^{-2}.
3. Plant type: moderately erect type with moderate tillering capacity; after filling, panicle top about 60 cm from the ground; erect-leaved canopy without appearance of the panicles.
4. Panicle weight and number: grain weight per panicle is 5 g; 2.7 million panicles ha^{-1}.
5. Leaf area index (LAI) and ratio of leaf area to grains: the LA1 is about 6.5 based on the

three uppermost leaves; the ratio of leaf area to grain weight was 100:2.3, meaning that to produce 2.3 g of rice, 100 cm^2 of the upper three functional leaves are needed.

6. Harvest index: above 0.55.

Strategies for breeding super high-yielding hybrid rice

According to the basic principles of hybrid rice breeding, there are two ways to obtain super high yield, i.e., (1) to make full use of the dominant complementary effects of the two parents to improve morphological characteristics of the hybrid; and (2) to extend the genetic diversity of parents to increase the heterosis level. The morphological features have been discussed earlier. The second aspect involves:

1. Utilization of intersubspecific heterosis

The heterosis of intersubspecific hybrids is much stronger than that of intervarietal hybrids. Therefore, utilization of intersubspecific hybrids is the most feasible approach for realizing super high yield. We have focused our efforts on using Pei'ai 64S as the major female parent for selecting super high-yielding combinations because Pei'ai 64S is an intermediate type between indica and japonica with good wide compatibility. In addition, its morphological characteristics are also desirable for high yield. Several pioneer hybrids of Pei'ai 64S have been certified for commercial use and some promising hybrids possessing super high yield potential, such as Pei'ai 64S/E32, are under yield trials. So it is highly possible to obtain super high-yielding combinations by using Pei'ai 64S.

In the long run, to exploit the heterosis of intersubspecific hybrids and improve the efficiency of breeding super high-yielding hybrid rice, we emphasize the development of various widely compatible lines especially with a broad spectrum of compatibility, including restorer lines and male sterile lines of indica type, japonica type, and the intermediate type with different growth durations. In this way, we will have abundant parental lines for various super high-yielding hybrids adaptable to different ecological environments.

2. Utilization of favorable genes from wild rice

In 1995 based on the molecular analysis and field experiments of a cooperative research program with Cornell University, we identified two favorable QTL genes (yld1 and yld2) from wild rice *(O. rufipogon)*. Each of the QTL genes contributed to a yield advantage of 18% over the high-yielding hybrid V64 (one of the most elite hybrids in China with a yield potential of 80 kg ha^{-1} day^{-1}). Using molecular marker-facilitated backcrossing and selection, the creation of near isogenic lines carrying the two QTL genes is under way.

3. Utilization of IRRI's new plant types

Dr. G. Khush of IRRI predicted that "These new plant types are likely to have 20% higher yield potential than the existing high-yielding indicas. The new plant types will be employed in developing indica-japonica hybrids, which may have a yield advantage of 20-25% over the best inbred lines. A combination of the two approaches may raise the yield potential of tropical rice by 50%."

In 1995, we planted 21 IRRI lines of the new plant types in Changsha. These lines showed very sturdy stems, big panicles, and low tillering capacity, but had many unfilled grains and low yield. The low yield may be due to the source, which was not rich enough to fill the large sink. Nevertheless, we expect IRRI's NPTs to be promising with further improvement. They could play an important role in hybrid rice breeding for super high-yielding rice in the future.

In situ conservation and restoration of a locally extinct population of common wild rice *(Oryza rufipogon)*

Jin Zhou and Jia-Kuan Chen
School of Life Science, Wuhan University. Hubei 430072, China

In situ conservation and restoration of *Oryza rujipogon,* a locally extinct common wild rice (CWR), was undertaken in the northern region of China.

The objectives of this study were:

- To monitor population dynamics of CWR at its northern range limit (Dongxiang [28°14'N, 116°36'E] and Jiangyong [25°05'N, 112°02'E]) and find out conditions and mechanisms of extinction;
- To rebuild a locally extinct population and restore the community in Chaling (26°50'N, 113°40'E) according to CWR's biological characteristics.

The extinction of CWR can be attributed to both human activities and biological defects of the crop itself. However, the former is the main cause of the crop becoming extinct.

Human activities include either destruction of the population or changing the CWR habitats by various actions.

The biological defects of CWR are lack of an effective mechanism for dispersal, severe loss of the seed bank, low transforming rate from seedlings to mature plants, and difficulty of the seedlings to compete with weed (especially *Isachne globosa* and *Leersia hexandra* var. *japonica*) populations.

Ongoing projects

There are two ongoing projects on CWR in the country:

- Study on conservation biology of major endangered plants in China, supported by the National Natural Science Foundation (1993-97)
- Study on population behavior and community restoration of common wild rice to its area of origin after local extinction, supported by the National Natural Science Foundation (1997-99)

Proposed cooperation with IRRI

To further research work on CWR, it is proposed that (1) an international symposium on *in situ* conservation techniques on wild relatives of crops be organized, and (2) a comparative study on populations of CWR in the central part of the distribution area be undertaken.

Studies on sustainable utilization of wild rice germplasm at Wuhan University

Guangcun He and Lihui Shu
College of Life Science, Wuhan University, Wuhan 430072, China

Rice is the most important cereal crop in the world. China produces more than 37% of the world's total rice. Wild rice forms an important portion of the rice germplasm. Some important genes for rice improvement are derived from wild rice. The establishment of monocultures of several modem varieties and their repeated use in breeding programs have resulted in genetic uniformity in cultivated rice populations. As the population increases and rice production areas decrease, wild rice utilization becomes more critical to rice improvement than ever before.

Genes introgressed from wild rice into cultivated rice have the advantages of efficient expression and more stability. Furthermore, a new variety developed through wide hybridization and protoplast fusion using wild rice as a gene donor is preferred by the public. Genes or quantitative trait loci for yield in wild rice will widen the genetic base and help to increase the yield potential of cultivated rice. On the other side, the ecological environment for natural wild rice populations has rapidly disappeared as industrialization proceeds. Simple and safe conservation methods are needed for long-term preservation of wild rice germplasm in large numbers.

Wuhan University has been engaged in research on sustainable utilization of wild rice for decades.

Ongoing research

Genetic evaluation of wild rice

By applying RAPD and microsatellite DNA markers, genetic diversity and relationships among wild rice genomes were studied. Results showed that the genetic base in wild rice is more diverse. A tendency for differentiation of indica and japonica types was found in wild rice. *O. meyeriana,* a wild rice found in China, is distantly related to other wild rice and classified as a separate group by molecular markers. The karyotype of *O. meyeriana* has been determined to be different from that of cultivated rice. The multiple resistance of *O. officinalis,* the bacterial blight resistance of *O. meyeriana,* and the overwintering ability of *O. rufipogon* have been evaluated.

Cryopreservation of wild rice

Cryopreservation of plant cells in iiquid nitrogen is a safe method for long-term conservation of germplasm. We successfully cryopreserved calluses of 11 species of wild rice; seven of them regenerated into plants after the composition of the cryoprotectant was modified. Experiments showed that there is a danger of somatic variation in plant cell culture in vitro. We developed a procedure to store young panicles of wild rice in nitrogen and directly regenerated the plant, not via callus. The method offers a selection of ways in which wild rice germplasm can be more efficiently maintained in the long term.

Tissue and cell culture

In the young panicle culture of wild rice, calluses were induced in 11 species studied; nine species were regenerated. The embryogenic property of wild rice callus was maintained through low temperature, desiccation, and change in ingredients of the subculture media. *O. meyeriana* is an important bacterial blight-resistant species but is difficult to grow in tissue culture. An embryogenic callus line was selected and embryogenic suspension was established. Protoplast plants were regenerated for this species.

Introgression of important genes

By sexual and somatic hybridization, hybrids of *O. sativa* and *O. rufipogon, O. latifolia, O. officinalis, O. minuta, O. redlev, O. granulata,* and *O. meyeriana* were produced. Several important genes were introgressed into cultivated rice, including a CMS gene from *O. rufipogon* (Honglian type); a gene with resistance to bacterial leaf blight from *O. rufipogon, O. latifolia,* and *O. officinalis;* and a brown planthopper resistance gene from *O. latifolia* and *O. foficinalis.* Resistant lines and CMS rice with improved plant type were developed and released to breeders and farmers for commercial production.

Inheritance and mapping studies

Bacterial blight resistance from *O. rufipogon* and *O. latifolia* were found to be controlled by one or two major genes, respectively. The spectrum of resistance to brown planthopper in an introgressed line from *O. latifolia* and *O. officinalis* was determined. The new BPH resistance gene is being mapped using the RFLP technique.

Prospects for cooperation

With decades of experiments and a solid foundation on wild rice research, Wuhan University will further its efforts in the conservation and sustainable utilization of wild rice germplasm. Genes controlling resistance, tolerance, CMS, and yield components will be continuously introgressed from wild rice into cultivated rice. In the process, molecular markers will be established for genes that will serve as a starting point for marker-aided selection programs and map-based gene cloning programs. Cooperation and support from domestic and overseas organizations will accelerate the research and contribute to improved rice production in China and worldwide.

Improving yield potential by modifying plant type

Gurdev S. Khush and Shaobing Peng
International Rice Research Institute, MCPO Box 3127, 7271 Makati City, Philippines

World food crops have been improved progressively since their domestication starting about 10,000 years ago. Progress was especially rapid after the rediscovery of Mendel's laws of inheritance when scientific principles could be applied to crop improvement. Modern varieties of wheat and rice which ushered in the Green Revolution and led to a doubling of cereal production in a 25-year period are examples of recent achievements in increasing crop productivity. The present world population of 5.9 billion is likely to reach 7 billion in 2010 and 8 billion in 2025. Per capita food intake will increase due to improved living standards. It is estimated that we will have to produce 50% more food by 2025. Food grain production in Africa will have to increase by almost 400%, in Latin America by 200%, and in Asia by 75%.

In the past, food production increased as a result of higher yield potential of new crop varieties as well as increases in cropped area. In the future, major increases in cropped area are unlikely. In fact, in most Asian countries, cultivated area is declining due to pressure from urbanization and industrialization. Use of pesticides is going down due to concerns about their harmful effects on the environment and human health. The increasing industrial base is competing with agriculture for water and labor. Thus, we will have to produce more food from less land, with less pesticides, less labor, and less water. Therefore, increases in crop productivity are essential to feed the world in the 21st century. One way to increase crop productivity is to develop crop cultivars with higher yield potential by modifying plant type.

Plant type breeding in retrospect

Selection for semidwarf stature in the late 1950s for rice and wheat is the most striking example of a successful improvement in plant type. Although selections were guided by short stature, resistance to lodging, and efficient biomass partitioning between grain and straw, breeders were unintentionally selecting for improved canopy architecture, light penetration, and other favorable agronomic characteristics (as reviewed by Takeda 1984). In pioneering studies, Tsunoda (1959) compared yield potential and the yield response to nitrogen (N) fertilizer of rice genotypes differing in plant type. Varieties with high yield potential and greater responsiveness to applied N had short sturdy stems and leaves that were erect, short, narrow, thick, and dark green. The close association between certain morphological traits and yielding ability in response to N led to the "plant type concept" as a guide for breeding improved varieties (Yoshida 1972).

IR8, the first high-yielding modern rice cultivar, was released by IRRI in 1966. This event marked the start of the Green Revolution in Asia. IR8 was a semidwarf with profuse tillering, stiff culm, erect leaves, photoperiod insensitivity, N responsiveness, and high harvest index (HI) compared with traditional cultivars (Chandler 1969). Development and adoption of high-yielding varieties like IR8 occurred rapidly in South, East, and Southeast Asia because farmers obtained a yield advantage of 1-2 t ha^{-1} on irrigated land over traditional varieties (Chandler 1972). Today, more than 60% of the world's rice area is planted to semidwarf plant types similar to IR8, and they account for more than 80% of total rice production (Khush 1990).

Donald (1 968) proposed the ideotype approach to plant breeding. In this approach, a plant type which is theoretically efficient based on knowledge of physiology and morphology is defined first. Breeders then select directly for the ideotype, rather than only for yield. Many ideotype traits such as plant height, tiller and panicle number, leaf orientation and color, and grain weight have, consciously or subconsciously, been selection targets in most cereal breeding programs (Rasmusson 1991). Studies of historic cultivars often show that genetic improvement in yield potential has resulted from increases in HI, which are associated with ideotype characters, e.g., short stature in rice and wheat and the uniculm habit in maize and sunflower (Sedgley 1991). Several attempts at ideotype breeding have been documented: low-tillering barley (Donald 1979), better light interception in peas (Hedley and Ambrose 198l), improved water-use efficiency in wheat (Richards and Passioura 1981), and multiple awn and high stomatal frequency in barley (Rasmusson 1991). The ideotype concept has led to a more physiological approach to yield improvement (Thurling 1991).

Past success in increasing yield potential has mainly been the result of an empirical selection approach, that is, selecting for yield per se (Loss and Siddique 1994). Further increases in yield potential are difficult to attain using the empirical selection approach because the crop has already reached a high yield potential (Slafer et a1 1996). It is expected that during the next decades genetic improvement of yield potential will be accelerated using physiological attributes as selection criteria (Shorter et a1 1991). The ideotype concept that initially emphasized simple morphological traits should be extended to physiological and biochemical levels (Hamblin 1993). Further modification of plant type based on new knowledge of physiology and biochemistry provides opportunities for increasing yield potential. The morphological traits to be modified should have a favorable influence on physiological processes that determine yield potential.

Yield-limiting factors and related morphological traits

Biomass production

Harvestable yield is the product of total biomass produced times HI. For cereal crops, genetic gain in yield potential usually resulted from improved HI through modified canopy architecture (Austin et a1 1980). Current high-yielding indica rice varieties have a yield potential of 10 t ha^{-1} with an HI of 0.5 under tropical irrigated conditions. It is difficult to further increase HI for many cereals (Austin et a1 1980), implying that a further increase in yield potential will be attained mainly through increased biomass production. This is indirectly supported by the fact that the yield of 13.6 t ha^{-1} was achieved with an HI of 0.46 in the temperate environment of Yunnan, China (Khush and Peng 1996).

Increased biomass production is not difficult to achieve when the rice crop is grown under a high solar radiation environment similar to dry-season conditions at IRRI, and provided with a luxuriant supply of N (Akita 1989). The maximum crop growth rate of rice is around 30-36 g m^{-2} d^{-1} in the Philippines (Yoshida and Cock 1971). Akita (1989) reported a crop growth rate of 40 g m^{-2} d^{-1} with a maximum leaf area index (LAI) of 20 in a high-N outdoor solution-culture system. Without a strong, thick culm and proper partitioning, however, increased biomass production results in lodging, mutual leaf shading, increased disease, and decreased grain yield (Vergara 1988). If lodging and disease problems can be solved, increased biomass production could contribute to increased yield potential in tropical environments.

Biomass production can be increased through optimized canopy architecture for maximum canopy photosynthesis. Canopy photosynthetic rate increases as leaf area index increases. The crop reaches optimum LAI when canopy photosynthesis levels off. An ideal variety should have a droopy canopy at the very early vegetative stage to effectively intercept solar radiation. As the crop grows, a plant community with vertically oriented leaves gives better light penetration and higher canopy photosynthetic rate at high LAI. Varieties with erect leaves have higher optimum LAI than varieties with horizontal leaves (Yoshida 1981). Light is used more efficiently at high LAI in an erect-leaved canopy (Yoshida 1976). Carbon assimilation of a leaf exposed to light on only one side is lower than when the leaf is exposed on both sides if total light intensity is equal for each case. This difference is greatest when leaves have high N content and greater thickness. Therefore, a plant community with vertically oriented leaves gives better light penetration and higher carbon assimilation per unit of leaf area (Tanaka 1976). Droopy or horizontally oriented leaves increase the relative humidity inside the canopy due to reduced air movement (Akiyama and Yingchol 1972). These changes in microclimate provide a more favorable canopy environment for many diseases and some insect pests of rice (Yoshida 1976). It was reported recently that V-shaped leaf blades reduce mutual shading and increase canopy photosynthesis as do erect leaves (Sasahara et a1 1992). A thick leaf has less tendency to expand horizontally and a greater tendency to be erect. Although a positive association between leaf thickness and yield potential has not been documented for rice, leaf thickness is positively correlated with leaf photosynthetic rate (Murata 1961). Thick leaves are therefore thought to be desirable (Yoshida 1972), and this trait provides a visual selection criterion for the new plant type.

Lowering panicle height increases light interception by leaves and consequently increases canopy photosynthesis (Setter et al 1995). The semidwarf plant type reduces susceptibility to lodging at high N inputs and increases HI (Tsunoda 1962). Shorter culms require less maintenance respiration and contribute to an improved photosynthesis-respiration balance (Tanaka et al 1966). However, recent studies indicated that the lower plant height of semidwarf rice and wheat may limit canopy photosynthesis and biomass production (Kuroda et al 1989, Gent 1995). A taller canopy has better ventilation and therefore higher CO_2 concentration inside the canopy. Light penetrates better in the tall than in the short canopy (Kuroda et a1 1989). Sedgley (1991) reported that increases in yield trend with year of release is associated with increasing plant height and reduced tillering capacity for wheat cultivars widely grown in Western Australia. If stem strength can be improved, the height of modem rice varieties should be increased to improve biomass production.

Sink size

The number of spikelets per unit land area is the primary determinant of grain yield in cereal crops grown in high-yield environments without stress (Takeda 1984). Current high-yielding varieties with a yield potential of 10 t ha^{-1} produce 45,000-50,000 spikelets m^{-2}, 85-90% of which are filled spikelets. About 60,000 filled spikelets m^{-2}, would be needed for a 15 t ha^{-1} yield with a 1000-grain weight of 25 g.

Sink size is determined by spikelet number per panicle and panicle number per square meter. Since a strong compensation mechanism exists between the two yield components, an increase in one component does not necessarily result in an increase in overall sink size. Sink size would be increased by selecting for large panicles only if the panicle number per square meter is maintained. The way to delink the strong negative relationship between the two components is to increase biomass production during the critical development phases when sink size is determined. Slafer et a1 (1996) recommended that breeders should select for greater growth during the time when grain number is determined rather than select for panicle size or number. The critical period that determines sink size was reported to be 20-30 days before flowering in wheat (Fischer 1985). In rice, spikelet number per square meter was highly related to dry matter accumulation during the period from panicle initiation to flowering (Kropff et al 1994). Akita (1989) said that there is a genotypic variation in spikelet formation efficiency (the number of spikelets produced per unit of growth from panicle initiation to flowering). To increase sink size, one should select for higher spikelet formation efficiency.

Fischer (1985) reported that accelerating development during active spike growth through increases in air temperature reduced the final number of grains in wheat. Slafer et al (1996) proposed to extend the stem elongation phase (from terminal spikelet initiation to flowering) to increase biomass accumulation in the same phase and final spikelet number. Temperature and photoperiod are the main environmental factors that affect development rate. Slafer and Rawson (1994) showed varietal differences in degree of sensitivity to temperature during stem elongation in wheat. Sheehy (1995, personal communication) observed that a large proportion of primordia were aborted in the tropical rice plant, probably due to fast development rate caused by high temperature or shortage in N uptake. Yoshida (1973) showed that the number of spikelets per panicle was reduced under high temperature. Several other approaches were suggested to increase sink size. Richards (1996) proposed to increase carbon supply to the developing panicles by reducing the size of competing sinks. This could be achieved by reducing the length of the peduncle (the internode between the uppermost leaf node and the panicle) and reducing unproductive tillers.

Increases in the yield potential of other cereals such as maize and sorghum have resulted from increases in sink size. Selection and breeding for large sink size were accompanied by a decrease in tiller number: modern maize and sorghum varieties are uniculm whereas primitive maize and sorghum have a large number of tillers and small cobs or heads (Khush 1990). In contrast, modem rice varieties tiller profusely. Although each rice hill includes 3-5 plants and produces 30-40 tillers under favorable growth conditions, only 15-16 produce panicles. Unproductive tillers compete with productive tillers for assimilates, solar energy, and mineral nutrients particularly nitrogen. Elimination of unproductive tillers could direct more nutrients to grain production, but the magnitude of the potential contribution to yield has not been quantified. Furthermore, the dense canopy that results from excess tiller production creates a humid microenvironment favorable for diseases, especially endogenous pathogens such as sheath blight and stem rot that thrive in N-rich canopies (Mew 1991).

Ise (1992) found that a single semidominant gene controlled the low tillering trait, and that this gene had pleiotropic effects on culm length and thickness, and panicle size. Therefore, the low tillering trait was hypothesized to be associated with larger panicle size. Reduced tillering is thought to facilitate synchronous flowering and maturity, more uniform panicle size, and efficient use of horizontal space (Janoria 1989). Clearly, an emphasis on larger panicle size would be needed to compensate for reduced panicle number in low-tillering plant types.

Grain filling

Grain weight is considered to be a stable varietal character in rice with less than 5% coefficient of variation among different years at the same site (Yoshida 1972). By contrast, yearly variation of grain weight in barley can be as large as 50% (Thorne 1966), and the variation of wheat grain weight as large as 30% (Asana and Williams 1965). On the other hand, Venkateswarlu et al (1986b) found 43% variation in the weight of single rice grains within a panicle. Since grain size is rigidly controlled by hull size in rice, the weight of fully filled spikelets is relatively constant for a given variety (Yoshida 198 1). Breeders rarely select for grain weight because of the negative linkage between grain weight and grain number. This does not mean, however, that there is no opportunity to increase rice yield potential by selecting for heavy grains. Major efforts should be directed at reducing the proportion of partially filled and empty spikelets by improving grain filling.

Filled spikelet percentage is determined by the source activity relative to sink size, the ability of spikelets to accept carbohydrates, and the translocation of assimilates from leaves to spikelets (Yoshida 1981). These factors determine the rate of grain filling. Akita (1989) reported a close relationship between crop growth rate at heading and filled spikelet percentage. Carbon dioxide enrichment during the ripening phase increased crop growth rate, filled spikelet percentage from 74% to 86%, and grain yield from 9.0 to 10.9 t ha^{-1} (Yoshida and Parao 1976). Increasing late-season N application led to increased leaf N concentration, photosynthetic rate, and grain yield (Kropff et al 1994).

The ability of spikelets to accept carbohydrates is often referred to as sink strength. Starch is reported to be a critical determinant of sink strength (Kishore 1994). Starch levels in a developing sink organ can be increased by increasing the activity of adenosine diphosphate (ADP) glucose pyrophosphorylase (Stark et a1 1992). Plant hormones such as cytokinins that regulate cell division and differentiation in the early stage of seed development also affect sink strength (Quatrano 1987). Application of cytokinin at and after flowering improved grain filling and yield of rice plants, probably through increased sink strength and/or delayed leaf senescence (Singh et a1 1984). The capacity of transporting assimilates from source to sink could also limit grain filling (Ashraf et a1 1994). Indica rice has more vascular bundles in the peduncle relative to the number of primary branches in the panicle than japonica rice (Huang 1988). It is not clear if the number of vascular bundles is more important than their size in terms of assimilate transport. Low-tillering varieties have more inner and outer vascular bundles and greater peduncle diameter and thickness just below the neck node than high-tillering varieties (Kim and Vergara 1991). The number of inner and outer vascular bundles was associated with a larger number of rachis-branches, and more spikelets and grain weight per panicle.

Simulation modeling suggests that prolonging grain-filling duration will result in an increase in grain yield (Kropff et al 1994). Varietal differences in grain-filling duration were reported by Senadhira and Li (1989), but only main culm panicles were compared in this study. It is not known if grain-filling duration differs among varieties within subspecies when the entire population of panicles is considered. Grain-filling duration is controlled mainly by temperature. Slafer et a1 (1996) proposed to increase grain-filling duration by manipulating response to temperature. Hunt et a1 (1991) reported genotypic variation in sensitivity to temperature during grain filling in wheat. Such variation in grain-filling duration in response to temperature has not been reported in rice.

High-density grains are those that remain submerged in a solution of specific gravity greater than 1.2. Regardless of the growth duration of varieties studied, the proportion of high-density grains was greatest (70-85%) at the top of the panicle (superior spikelet positions) and lowest (10-50%) in the inferior spikelets in the lower portion of the panicle (Padmaja Rao 1987a). High-density grains tend to occur on primary branches of the panicle, whereas spikelets of secondary branches had lower grain weight (Ahn 1986). The proportion of high-density grains was 15% greater in primary tillers than in secondary and tertiary tillers for short-duration cultivars (Padmaja Rao 1987b). Low-tillering genotypes are reported to have a larger proportion of high-density grains (Padmaja Rao 1987b). Varietal differences in number of high-density grains per panicle were reported, and this trait appeared to be heritable (Venkateswarlu et a1 1986b). Moreover, high-density grains also gave higher milling recovery and head rice yield (Venkateswarlu et a1 1986a).

Rice grain yield could be increased by 30% if all the spikelets of an 8-t ha^{-1} crop were high-density grains (Venkateswarlu et a1 1986b). The hypothesis that selection for high-density grain types would result in greater yield potential assumes that there is sufficient assimilate or source to make heavier grains. In a more recent work, Iwasaki et a1 (1992) found that superior spikelets are the first to accumulate dry matter and nitrogen during grain filling; inferior spikelets do not begin to fill until the dry weight accumulation in superior spikelets is nearly finished. This apical dominance within the panicle can be altered immediately upon removal of superior spikelets, which indicates that the delayed filling of inferior spikelets results from a source limitation and regulation of the assimilate allocation within the panicle. It is not known if overall grain filling can be improved by weakening this apical dominance.

Lodging

It is impossible to further increase the yield potential of irrigated rice without improving its lodging resistance. The types of lodging are bending or breakage of the shoot and root upheaval (Setter et a1 1994). Lodging reduces grain yield through reduced canopy photosynthesis, increased respiration, reduced translocation of nutrients and carbon for grain filling, and greater susceptibility to pests and diseases (Hitaka 1969). Leaf sheath wrapping, basal internode length, and the cross-sectional area of the culm are the major plant traits that determine straw strength (Chang and Vergara 1972). The relative importance of each factor depends partly on the time of lodging. Leaf sheaths support the whole plant until internode elongation starts. Even after the completion of internode elongation, leaf sheaths contribute to the breaking strength of the shoot by 30-60% (Chang 1964). Therefore the sheath biomass and extent of wrapping will always be an important trait for selection against lodging at all developmental stages (Setter et a1 1994). Ookawa and Ishihara (1992) reported that the breaking strength of the basal internode was doubled due to leaf sheath covering and was tripled because of the large area of the basal internode cross-section.

Terashima et a1 (1995) found that greater root mass and more roots distributed in the subsoil (where soil bulk density is high) were associated with increased resistance to root lodging in direct-seeded rice. Further reductions in stem height of semidwarf varieties are not a good approach to increase lodging resistance because this will cause a decrease in biomass production. Lowering the panicle height could have a profound effect on increasing lodging tolerance because the height of the center of gravity of the shoot is reduced (Setter et a1 1995). Ookawa et a1 (1993) studied the composition of cell wall materials in the fifth internode of different rice varieties under different growing conditions and found that the densities of lignin, glucose, and xylose were associated with stem strength.

Breeding for a new rice plant type

Semidwarf rice produces a large number of unproductive tillers and has excessive leaf area, which cause mutual shading and reduce canopy photosynthesis and sink size, especially when it is grown under direct-seeded conditions. Simulation modeling indicated that a 25% increase in yield was possible if the following traits were modified in the current high-yielding plant types (Dingkuhn et a1 1991): (1) enhanced leaf growth combined with reduced tillering during early vegetative growth, (2) reduced leaf growth along with sustained high foliar N concentration during late vegetative and reproductive growth, (3) a steeper slope of the vertical N concentration gradient in the leaf canopy with more N present at the top, (4) an expanded storage capacity of stems, and (5) an improved reproductive sink capacity along with an extended grain-filling period.

To break through the yield potential barrier, IRRI scientists proposed modifications to the present high-yielding plant type. Although the proposed characteristics of the new ideotype came from several different perspectives (Vergara 1988, Janoria 1989, Dingkuhn et a1 1991), the major components included essentially the following: (1) low tillering capacity (3-4 tillers when direct seeded), (2) no unproductive tillers, (3) 200-250 grains per panicle, (4) very sturdy stems, (5) dark green, thick and erect leaves, (6) vigorous root system, and (7) increased harvest index. Peng et a1 (1994) reviewed these individual traits in relation to yield potential. However, an in-depth scientific evaluation of the proposed new ideotype has not been conducted.

This ideotype became the “new plant type” highlighted in IRRI’s strategic plan (IRRI 1989a), and the breeding effort to develop this germplasm became a major core research project of the 1990-94 work plan (IRRI 1989b) and in the 1994-98 medium-term plan (IRRI 1993). The goal was to develop a new plant type (NPT) with higher yield potential than existing semidwarf varieties in a tropical environment. Breeding work on the NPT was started in 1989 when about 2000 entries from the IRRI germplasm bank were grown during the dry (DS) and wet seasons (WS) to identify donors for various traits (Khush 1995). Donors for low tillering trait, large panicles, thick stems, vigorous root system, and short stature were identified. They are mainly bulus or javanicas from Indonesia, which are now referred to as tropical japonicas (Khush 1995). Hybridization work was undertaken in 1990 DS and F_1 progenies were grown for the first time in 1990 WS, F_2 progenies in 1991 DS, and a pedigree nursery in 1991 WS. Since then, more than 2100 crosses have been made, and 110,000 pedigree lines have been produced. Breeding lines with targeted traits of the proposed ideotype have been selected. They were grown in an observational trial for the first time in 1993 WS. Their morphophysiological traits and yield potential have been evaluated since 1994 DS in replicated field plots under various management practices (Khush and Peng 1996).

After evaluating the NPT lines for three seasons at three locations, the following points can be summarized:

1. The tropical japonicas have been improved into NPT lines in less than 5 years. The test NPT lines did not yield well due to poor grain filling. However, we have evaluated only a few of the large number of NPT lines. New crosses are being made and more NPT lines will be available soon. Selection pressure for good grain filling will be applied in the early generations. Research on NPT will be continued with the goals of breaking the yield barrier and increasing germplasm diversification.
2. Among the NPT lines tested, IR65598-112-2 consistently performed better than the others. Its sink size is 10-15% higher than indica inbred checks. It has large panicles and its morphological traits resembled the ideotype proposed in 1989 by IRRI scientists. This partially proves that the major aspects of the NPT design were correct.
3. Low biomass production, poor grain filling, and pest susceptibility are the major constraints to yields of NPT lines. The cause and effect relationship between low biomass production and poor grain filling needs to be determined. It is unlikely that only poor grain filling causes low biomass production, since low growth rate was observed between panicle initiation and flowering and during the ripening phase.
4. Nitrogen concentration and photosynthetic rate on a single-leaf level of the NPT lines showed no disadvantage compared with semidwarf indica varieties. Lower canopy photosynthetic rate and biomass production might be largely attributed to less tillering. Lines with slightly higher tiller numbers are being selected.
5. Compact panicle, lack of apical dominance, and limited large vascular bundles are associated with poor grain filling in NPT lines. Selection for long panicles, while maintaining a large sink size, may partially improve grain filling in NPT lines.
6. Panicle size (i.e., spikelets per panicle) decreased more in NPT lines than in semidwarf indica varieties when panicle number increased. This partially explains why NPT lines did not perform better under direct-seeded than under transplanted conditions.

Based on these findings, we have taken the following measures to improve NPT lines:

1. Introduction of indica genes. Hybridization between NPT lines and indica inbreds is in progress. Lines intermediate between tropical japonicas and indicas could overcome some problems of NPT lines such as grain filling and pest resistance. In the meantime, some NPT lines will be kept purely in japonica background for developing indica/japonica F_1 hybrid rice.
2. Selection of parents with good grain filling. We have measured the grain filling of most parental lines for developing NPT lines. New crosses have been made with parents that have high grain-filling percentage. It seems that grain filling is a heritable trait among the test tropical japonica germplasm.
3. Modification of traits. We have slightly modified the previous design of NPT with moderate increases in tillering capacity, plant height, and growth duration, and a slight decrease in panicle size.
4. Selection criteria. In the selection process, grain-filling percentage, biomass production at flowering, and number of large vascular bundles are being used as selection criteria in addition to grain yield.
5. Pest resistance and grain quality. Resistance to tungro and brown planthopper is being incorporated into NPT lines. We also need to improve grain quality. Donors for these traits have been identified and are being used in the hybridization program.

References

Ahn JK. 1986. Physiological factors affecting grain filling in rice. PhD thesis, University of the Philippines Los Baños, Laguna, Philippines. 127 p.

Akita S. 1989. Improving yield potential in tropical rice. In: Progress in irrigated rice research. Los Baños, Philippines: IRRI. p 41-73.

Akiyama T, Yingchol P. 1972. Studies on response to nitrogen of rice plant as affected by difference in plant type between Thai native and improved varieties. Proc. Crop Sci. Soc. Japan 41, 126-132.

Asana RD, Williams RF. 1965. The effect of temperature stress on grain development in wheat. Aust. J. Agr. Res. 16, 1-13.

Ashraf M, Akbar M, Salim M. 1994. Genetic improvement in physiological traits of rice yield. In: Genetic improvement of field crops. Slafer GA, editor. New York: Marcel Dekker, Inc. p 413-455.

Austin RB, Bingham J, Blackwell RD, Evans LT, Ford MA, Morgan CL, Taylor M. 1980. Genetic improvements in winter wheat yields since 1900 and associated physiological changes. J. Agric. Sci. (Cambridge) 94,675-689.

Chandler RFJr. 1969. Plant morphology and stand geometry in relation to nitrogen. In: Physiological aspects of crop yield. Eastin JD, Haskins FA, Sullivan CY, van Bavel CHM, editors. Madison, Wisconsin: ASA. p 265-285.

Chandler RFJr. 1972. The impact of the improved tropical plant type on rice yields in South and Southeast Asia. In: Rice breeding. Los Baños, Philippines: IRRI. p 77-85.

Chang TT. 1964. Varietal differences in lodging resistance. Int. Rice Comm. Newsl. 13, 1-11.

Chang TT, Vergara BS. 1972. Ecological and genetic information on adaptability and yielding ability in tropical varieties. In: Rice breeding. Los Baños, Philippines: IRRI. p 431-453.

Dingkuhn M, Penning de Vries FWT, De Datta SK, van Laar HH. 1991. Concepts for a new plant type for direct-seeded flooded tropical rice. In: Direct-seeded flooded rice in the tropics. Los Baños, Philippines: IRRI. p 17-38.

Donald CM. 1968. The breeding of crop ideotypes. Euphytica 17,385-403.

Donald CM. 1979. A barley breeding programme based on an ideotype. J. Agric. Sci. 93,261-269.

Fischer RA. 1985. Number of kernels in wheat crops and the influence of solar radiation and temperature. J. Agric. Sci. 100,447-461.

Gent MPN. 1995. Canopy light interception, gas exchange, and biomass in reduced height isolines of winter wheat. Crop Sci. 35, 1636-1642.

Hamblin J. 1993. The ideotype concept: useful or outdated? In: International crop science I. Madison, Wisconsin: Crop Science Society of America. p 589-598.

Hedley CL, Ambrose MJ. 1981. Designing "leafless" plants for improving yields of the dried pea crop. Adv. Agron. 34,225-277.

Hitaka H. 1969. Studies on the lodging of rice plants. JARQ 4, 1-6.

Huang H. 1988. Japonica and indica differences in large vascular bundles in culm. Intl. Rice Res. Newsl. 13, 7.

Hunt LA, van der Poorten G, Pararajasingham S. 1991. Post-anthesis temperature effects on duration and rate of grain filling in some winter and spring wheats. Can. J. Plant Sci. 71,609-617.

IRRI. 1989a. IRRI toward 2000 and beyond. Los Baños, Philippines: IRRI.

IRRI. 1989b. Implementing the strategy: work plan for 1990-1994. Los Baños, Philippines: IRRI. p 15-17.

IRRI. 1993. Rice research in a time of change: IRRI's medium-term plan for 1994- 1998. Los Baños, Philippines: IRRI. p 35-36.

Ise K. 1992. Inheritance of a low-tillering plant type in rice. Intl. Rice Res. Newsl. 17, 5.

Iwasaki Y, Mae T, Makino A, Ohira K, Ojima K. 1992. Nitrogen accumulation in the inferior spikelet of rice ear during ripening. Soil Sci. Plant Nutr. 38,517-525.

Janoria MP. 1989. A basic plant ideotype for rice. Intl. Rice Res. Newsl. 14, 12-13.

Khush GS. 1990. Varietal needs for different environments and breeding strategies. In:

New frontiers in rice research. Muralidharan K, Siddiq EA, editors. Hyderabad (India): Directorate of Rice Research. p 68-75.

Khush GS. 1995. Breaking the yield frontier of rice. GeoJournal 35, 329-332.

Khush GS, Peng S. 1996. Breaking the yield frontier of rice. In: Increasing yield potential in wheat: breaking the barriers. Reynolds MP, Rajaram S, McNab A, editors. Lisboa (Mexico): International Maize and Wheat Improvement Center. p 36-5 I.

Kim JK, Vergara BS. 1991. Morpho-anatomical characteristics of different panicles in low and high tillering rices. Korean J. Crop Sci. 36,568-575.

Kishore GM. 1994. Starch biosynthesis in plants: identification of ADP glucose pyrophosphorylase as a rate-limiting step. In: Breaking the yield barrier. Cassman KG, editor. Los Baiios, Philippines: IRRI. p 117-119.

Kropff MJ, Cassman KG, Peng S, Matthews RB, Setter TL. 1994. Quantitative understanding of yield potential. In: Breaking the yield barrier. Cassman KG, editor. Los Baiios, Philippines: IRRI. p 21-38.

Kuroda E, Ookawa T, Ishihara K. 1989. Analysis on difference of dry matter production between rice cultivars with different plant height in relation to gas diffusion inside stands. Jpn. J. Crop Sci. 58, 374-382.

Loss SP, Siddique KHM. 1994. Morphological and physiological traits associated with wheat yield increases in Mediterranean environments. Adv. Agron. 52,229-276.

Mew T. 199 1. Disease management in rice. In: CRC handbook of pest management in agriculture. 2nd ed., Vol. III. Pimentel D, editor. Boston: CRC Press Inc. p 279-299.

Murata Y. 1961. Studies on the photosynthesis of rice plants and its cultural significance [in Japanese, English summary]. Bull. Natl. Inst. Agr. Sci. Jpn. Ser. D, 9,l-169.

Ookawa T, Ishihara K. 1992. Varietal difference of physical characteristics of the culm related to lodging resistance in paddy rice. Jpn. J. Crop Sci. 61,419-425.

Ookawa T, Todokoro Y, Ishihara K. 1993. Changes in physical and chemical characteristics of culm associated with lodging resistance in paddy rice under different growth conditions and varietal difference of their changes. Jpn. J. Crop Sci. 62,525-533.

Padmaja Rao S. 1987a. Panicle type: few structural considerations for higher yield potential in rice. Indian J. Plant Physiol. 30, 87-90.

Padmaja Rao S. 1987b. High density grain among primary and secondary tillers of short- and long-duration rices. Intl. Rice Res. Newsl. 12, 12.

Peng S, Khush GS, Cassman KG. 1994. Evolution of the new plant ideotype for increased yield potential. In: Breaking the yield barrier. Cassman KG, editor. Los Baiios, Philippines: IRRI. p 5-20.

Quatrano RS. 1987. The role of hormones during seed development. In: Plant hormones and their role in plant growth and development. Davies PJ, editor. Kluwer Academic Publishers. p 494-514.

Rasmusson DC. 1991. A plant breeder's experience with ideotype breeding. Field Crops Res. 26, 191-200.

Richards RA. 1996. Increasing the yield potential of wheat: Manipulating sources and sinks. In: Increasing yield potential in wheat: breaking the barriers. Reynolds MP, Rajara S, McNab A, editors. Lisboa (Mexico): International Maize and Wheat Improvement Center. p 134- 149.

Richards RA, Passioura JB. 1981. Seminal root morphology and water use of wheat. I. Environmental effects. Crop Sci. 21, 249-252.

Sasahara T, Takahashi T, Kayaba T, Tsunoda S. 1992. A new strategy for increasing plant productivity and yield in rice. Intl. Rice Comm. Newsl. 41, 1-4.

Sedgley RH. 1991. An appraisal of the Donald ideotype after 21 years. Field Crops Res. 26:93-112.

Senadhira D, Li GF. 1989. Variability in rice grain-filling duration. Intl. Rice Res. Newsl. 14, 8-9.

Setter TL, Conocono EA, Egdane JA, Kropff MJ. 1995. Possibility of increasing yield potential of rice by reducing panicle height in the canopy. I. Effects of panicle on light interception and canopy photosynthesis. Aust. J. Plant Physiol. 22,441-451.

Setter TL, Peng S, Kirk GJD, Virmani SS, Kropff MJ, Cassman KG. 1994. Physiological considerations and hybrid rice. In: Breaking the yield banier. Cassmar KG, editor. Los Baños, Philippines: IRRI. p 39-62.

Shorter R, Lawn RJ, Hammer GL. 1991. Improving genotypic adaptation in crops — a role for breeders, physiologists and modelers. Exp. Agric. 27, 155-175.

Singh G, Singh S, Gurung SB. 1984. Effect of growth regulators on rice productivity. Trop Agric. 61, 106-108.

Slafer GA, Calderini DF, Miralles DJ. 1996. Yield components and compensation in wheat: opportunities for further increasing yield potential. In: Increasing yield potentia in wheat: breaking the barriers. Reynolds MP, Rajaram S, McNab A, editors. Lisboa (Mexico): International Maize and Wheat Improvement Center. p 101-133.

Slafer GA, Rawson HM. 1994. Sensitivity of wheat phasic development to major environmental factors: a reexamination of some assumptions made by physiologists and modelers. Aust. J. Plant Physiol. 21, 393-426.

Stark DM, Timmerman KP, Barry GF, Preiss J, Kishore GM. 1992. Regulation of the amount of starch in plant tissues by ADP glucose pyrophosphorylase. Science 258, 287-292.

Takeda T. 1984. Physiological and ecological characteristics of high-yielding varieties of lowland rice. In: Proc. Intl. Crop Science Symposium, 17-20 Oct. Fukuoka, Japan.

Tanaka A, Kawano K, Yamaguchi J. 1966. Photosynthesis, respiration, and plant type of the tropical rice plant. IRRI Tech. Bull. No. 7.46 p.

Tanaka T. 1976. Regulation of plant type and carbon assimilation of rice. JARQ 10, 161-167.

Terashima K, Akita S, Sakai N. 1995. Physiological characteristics related with lodging tolerance of rice in direct sowing cultivation. III. Relationship between the characteristics of root distribution in the soil and lodging tolerance. Jpn. J. Crop Sci. 64, 243-250.

Thorne GN. 1966. Physiological aspects of grain yield in cereals. In: The growth of cereals and grasses. Milthorpe FL, Ivins JD, editors. London: Butterworths. p 88-105.

Thurling N. 1991. Application of the ideotype concept in breeding for higher yield in the oilseed brassicas. Field Crops Res. 26, 201-219.

Tsunoda S. 1959. A developmental analysis of yielding ability in varieties of field crops. II. The assimilation-system of plants as affected by the form, direction and arrangement of single leaves. Jpn. J. Breed. 9,237-244.

Tsunoda S. 1962. A developmental analysis of yielding ability in varieties of field crops. IV. Quantitative and spatial development of the stem-system. Jpn. J. Breed. 12, 49-56.

Venkateswarlu B, Parao FT, Visperas RM, Vergara BS. 1986a. Screening quality grains of rice with a seed blower. SABRAO J. 18, 19-24.

Venkateswarlu B, Vergara BS, Parao FT, Visperas RM. 1986b. Enhanced grain yield potentials in rice by increasing the number of high density grains. Philipp. J. Crop Sci. 11, 145-152.

Vergara BS. 1988. Raising the yield potential of rice. Philipp. Technol. J. 13, 3-9.

Yoshida S. 1972. Physiological aspects of grain yield. Annu. Rev. Plant Physiol. 23,437-464.

Yoshida S. 1973. Effects of temperature on growth of rice plant (*Oryza sativa* L.) in a controlled environment. Soil Sci. Plant Nutr. 19,299-310.

Yoshida S. 1976. Physiological consequences of altering plant type and maturity. In: Proc. Intl. Rice Res. Conf. Los Baños, Philippines: IRRI.

Yoshida S. 1981. Fundamentals of rice crop science. Los Baños, Philippines: IRRI.

Yoshida S, Cock JH. 1971. Growth performance of an improved rice variety in the tropics. Intl. Rice Comm. Newsl. 20, 1-15.

Yoshida S, Parao FT. 1976. Climatic influence on yield and yield components of lowland rice in the tropics. In: Climate and rice. Los Baños, Philippines: IRRI. p 471-494.

Pest management research into the next millennium

Paul S. Teng, Twng Wah Mew, Kong Leun Heong, Hei Leung, Michael Cohen,
and Kenneth Schoenly
International Rice Research Institute, MCPO Box 3 127, 1271 Makati City Philippines

The past four decades brought about tremendous changes in Asian agriculture, especially the introduction of new technologies for rice farming, which led to the Green Revolution and to the avoidance of famine in large parts of the continent. These new technologies include high-yielding rice cultivars, irrigation, synthetic fertilizers, and pesticides (insecticides, fungicides, and herbicides). In general, positive effects have resulted from most of the new technologies. However, there has been increased recognition that these new technologies cannot be generally applied, and that negative effects on the rice system itself and on the external environment may result if local needs are not considered in applying the new technologies (Teng, Fischer, and Hossain 1995).

The stability of rice production is continually challenged by chronic pest infestations and by pest outbreaks caused by the breakdown of cultivar resistance or by disruptions in natural control mechanisms caused by factors such as inclement weather, changes in husbandry practices, or overuse of broad-spectrum pesticides. The need to increase rice yields requires that pest management practices be developed that will minimize chronic pest losses and avoid pest outbreaks. If they are to be adopted and sustained, pest management practices need to fit into the socioeconomic environment of the particular farming community and utilize indigenous natural resources and existing know-how of farmers.

With pest management, the widespread use of insecticides has certainly been questioned, as well as the deployment over large areas of genetically homogenous cultivars. Ideas and practices that were considered sacrosanct by pest management practitioners in the 1960s and 1970s have now been challenged and some found invalid. Furthermore, in the 1990s, the role of farmers in decision-making and their empowerment to make decisions have received much attention. Several examples now refute a global, top-down approach to pest control. In its place, participatory approaches are increasingly being used by social scientists during the process to develop pest management knowledge. Indeed, the increased role of social science in pest management is a significant change in doing research that leads to sustainable practices for pest management. China has not been separated from these changes, especially since it is a founding member of the IPM Network coordinated by IRRI. Furthermore, while much disciplinary research is ongoing in excellent institutions throughout China to generate new discoveries, there has also been a move to conduct interdisciplinary, problem-solving research of the type needed to improve farmer practices at the field level.

In this paper, we focused on providing an overview of significant changes in pest management research and application in Asia, and making specific suggestions for future research in China. Specifically, our paper (a) reviewed some of the changes in concepts, knowledge, and technologies in pest management in the recent past, and (b) identified and discussed some new research areas that could lead to improved pest management in response to changes in China's agriculture.

Changes in concepts, knowledge, and technologies in rice pest management

Redefining important pests

The importance of pests to rice production may be considered from the viewpoints of their effects on either total yield (production per hectare, averaged over several seasons) or yield stability (variation in production per hectare, standard deviation for several seasons). Conceptually this implies that it is not only the magnitude of loss, but also the frequency of loss that must be considered in pest management. Changes in the composition and type of pests have also been recorded from among the species known to affect rice. For example, rice-associated fauna were found to number about 800 species, including related invertebrate taxa (spiders, mites, crustaceans, mollusks, other invertebrates), in recent community-wide surveys in the Philippines and Indonesia (Schoenly et a1 1996, Settle et a1 1996). Of the approximately 100 species of insects, 74 pathogens, and 1800 weeds commonly considered to be pests, less than 30 insects, 16 diseases, and 15 weeds are considered capable of causing economic losses (Teng 1994). Of these, an even smaller number are known to cause actual economic losses in farmers' fields on a regular basis! However, it was not until recently that the issue of which pest requires farmer action has been raised (Heong, Teng, and Moody 1999, although rice scientists in many countries have observed that some insects or pathogens develop into key pests when agricultural production practices change. The brown planthopper (BPH) and sheath blight (ShB) are two examples of Green Revolution pests. The former arises from inappropriate use of insecticides and its consequences on predator-prey relationships, and the latter arises from mismanagement of the rice crop through inordinately high plant densities and fertilizer use. It was common until recently in many countries to provide "national" recommendations to spray insecticides against key pests in a prophylactic manner, to view insecticides as part of the production package needed to grow high-yielding varieties, and to ignore any locality-dependent phenomena, including whether such pests were present.

One of the most important changes in thinking about key pests is that they do evolve with the rice system in toto, and that nothing short of systematic field observations via surveys will allow quantification of their ability to cause yield losses. Techniques recently tested on rice, such as correspondence analysis, allow the linking of rice production situations and specific pest species or sets of pests, and, furthermore, the influence of farmer characteristics on the relationship (Savary et al 1994). Results from several parts of Asia show that the features of any rice production system have a major influence on the complex of pests that could cause differences between attainable and actual yields obtained by a farmer, and that it would be illogical to make recommendations for pest management that are not specific to a production system.

In the 1970s, insects considered to be pests and to regularly cause yield losses if no control measures were applied included defoliators such as armyworms and leaffolders, BPH, the green leafhopper (GLH), stem borers, gall midge, and several grain-sucking insects. Diseases considered critical to control were blast, brown spot, tungro (in the tropics and subtropics), bacterial blight, and narrow brown spot. The current thinking based on new data from physiological experiments, field surveys, and computer simulations is that, in general, only a small fraction of rice fields in any year is threatened by any insect, that some insects do not occur in nature at populations capable of causing economic losses (e.g., early season leaffolders), and that there is a high level of natural control of many pests unless "abnormal" phenomena occur (e.g., BPH outbreaks caused by unexpected migration due to weather). Diseases such as brown spot and narrow brown spot have been shown incapable of causing economic losses even though damage may appear severe, whereas sheath blight has grown in importance due to a general shortening in height of modem rice cultivars (Heong, Teng, and Moody 1995).

Crop losses in rice were estimated in the 1960s to be 34% by insect pests, 10% by diseases, and 11% by weeds (Cramer 1967). These generalized figures are now considered to be valid only as potential loss figures for that period under the worst-case scenario, and not average, actual field losses in farmers' fields. In a more recent study in several Asian countries, average total loss in attainable rice yield caused by all factors (abiotic and biotic) was estimated to be 23%, of which pests (insects, diseases, and weeds) caused only 7% loss. Abiotic factors such as problem soils, drought, floods, and inclement weather were found to cause higher losses (Evenson et al 1996). For China, the study found that, for imgated, single-crop rice at an average, actual yield of 6.0 t ha^{-1}, about 92 and 88 kg ha” were accounted for by insects and diseases, i.e., 1.5% and 1.4%, respectively. This study had its own limitations as well since it could not discount the role of host plant resistance and other techniques. The figures therefore represented losses in spite of whatever pest management practices were being used by farmers.

In working with our Chinese counterparts, IRRI scientists believe that the target pests for potential collaboration, from which we can jointly contribute to making an impact, are stem borers, blast, and bacterial blight.

Unnecessary use of pesticides

Most farmers adopt pesticides as their main pest control tactic, particularly to prevent pest infestations. In many cases, these pesticide applications are unnecessary and are unlikely to result in economic returns on investment. In the Philippines, an analysis of farmers' insecticide applications showed that about 80% of the sprays were misuses, applied at the wrong time for the wrong targets (Heong et al 1995). A large proportion of the insecticides were targeted at leaf-feeding insects that infest the crop in the early growth stages. The most common species is the rice leaffolder, which causes highly visible damage symptoms. Farmers often perceive that these pests are damaging and yield-reducing and apply insecticides primarily to kill them. For this purpose, inexpensive and highly toxic chemicals (WHO Category I), such as methyl parathion, monocrotophos, and methamidophos, are frequently used.

On the other hand, research has shown that common leaf-feeding insects often attack the rice crop during the vegetative stage, but rarely in sufficiently high densities to cause yield reductions. Even when all hills were damaged by whorl maggots, making the crop look miserable, no yield loss could be detected (Vijante and Heinrichs 1986). For leaffolders, a larva could consume about 26 cm^2 or about 40% of the leaf. Incorporating this feeding rate, the rice model MACROS predicted yield decline when the larval density reached 15 per hill (Fabellar et al 1994). Normal larval densities are well below 3 per hill (Gou 1990, De Kraker 1996). Thus, insecticides applied in rice fields during the early crop stages are unlikely to be economically beneficial to farmers. Instead, they can cause ecological disruptions to the herbivore-predator balance favoring population developments of brown planthoppers (Way and Heong 1994, Heong and Schoenly 1997).

Similarly, farmers' fungicide applications are not optimal. In a recent survey of 633 farmers in Long An province, Vietnam, about 98% of the farmers sprayed at a symptom known locally as “yellow leaf disease” (Mai et al 1997). Researchers have not established the main cause of this symptom but have ruled out fungi, bacteria, and virus as the causal agent. Thus, sprays of benomyl (37%), hexaconazole (30%), carbendazin (9%), and validamycin (8%) were unlikely to be beneficial. The other disease commonly sprayed at was sheath blight. Farmers often applied their sprays when the symptoms were highly visible, which probably had poor efficacy.

For herbicide use, researchers found farmers' choice and timing of applications far from optimal (Meenakanit and Vongsaroj 1997, Moody et al 1997). Perhaps in this case, misuse from wrong timing of sprays may be limited because such sprays can negatively affect the crop.

Farmers' insecticide use does not seem to be based on economic rationale (Waibel 1986, Rola and Pingali 1993). Instead, these decisions made under conditions of uncertainty are influenced by their perceptions of the pest problem and expected benefits. These decisions seem to be more behavioral in nature. Thus, opportunities to integrate decision sciences, especially behavioral decision models, into pest management research can be a rich area for further investigation.

Deploying rice cultivars containing major genes for disease resistance

The widespread use of genetically uniform cultivars with major resistance genes for disease control has been considered a contributing factor to the "boom-and-bust'' cycle in agriculture. Such genetic vulnerability was well demonstrated by the 1970's epidemics of southern corn leaf blight in maize caused by the susceptibility of the Texas cytoplasm widely used for hybrid maize production in the United States (Tatum 1971).

In rice, blast epidemics resulting from a loss of host resistance have been common. The collapse of many Korean cultivars due to blast in the 1970s is a reminder of the vulnerability of relying on limited resistance sources for disease control. The issue of genetic vulnerability is particularly relevant to rice production in China considering the scale of production and the predominance of hybrid rice with a relatively narrow genetic base. Thus, strategic research built upon new knowledge from different pathosystems should be the priority in developing an integrated disease management program across different rice-growing regions in China.

In formulating a strategy of deploying host plant resistance for disease control, two often-debated issues deserve special emphasis. First, what are the relative merits of using major gene resistance? Despite the breakdown of some resistance genes, monogenic resistance, because of its strong effect and ease of manipulation, continues to represent a valuable genetic resource for crop protection. Indeed, examples of effective and durable major resistance genes are known in rice. The effective control of bacterial blight in China is in large part attributed to the extensive deployment of a few resistance genes, notably *Xa4*. Major genes have also been shown to be durable in several pathosystems (e.g., stem rust resistance genes, *Sr2, Sr26, Sr24,* and *Sr36* in wheat, McIntosh 1992). However, for the rice blast pathosystem, in which the pathogen is highly adaptive, major gene resistance is not adequate. In this case, broad-spectrum resistance is needed as insurance. Recently, Wang et a1 (1994) showed that the broad spectrum and durability of blast resistance in rice cultivar Moroberekan are associated with multiple major and minor genes. Thus, the optimal strategy is to combine "high-quality" major resistance genes in a background of nonpathogen-specific quantitative resistance.

Second, deployment of resistance genes needs to be done in the broad context of crop production. Since a primary concern of farmers is crop productivity, it is inevitable that farmers prefer a few selected rice cultivars with superior performance. Consequently, cultivars such as IR36 and IR64, with broad adaptability and yielding potential, tend to dominate. Diversification of resistance sources must therefore be done in conjunction with an active breeding program, recognizing that only gene combinations properly introgressed into superior agronomic types would be of practical use to farmers.

The research focus on host plant resistance therefore lies in the identification and deployment of effective and diverse resistance sources. Progress in several areas of molecular biology and microbial genetics is particularly relevant to this effort.

Biological control of pathogens

Chinese farmers have used tillage, crop rotation, and green manure for about 5000 years, with irrigation having started about 3000 years ago. According to literature, farmers were advised since 1 BC to practice fallowing if crop production was poor in the second year. It is reasonable, therefore, to believe that practices such as crop rotation and green manure application would enhance the biological control of soilborne diseases (Tang and Yang 1997).

Modem biological control research did not start until the 1950s. In 1954, a strain of *Streptomyces jingyangensis* designated as 5406 was isolated from a cotton/alfalfa field and eventually used to control diseases caused by *Rhizoctonia* and *Verticillium albo-atrum* over the next 30 years. Since then, progress in biological control did not make much headway due to problems of mass production of actinomyces. The main effort turned to antibiotics produced by a strain of *Streptomyces* sp. Jingangmycin, isolated by the Shanghai Pesticide Institute, which was found to be effective against sheath blight of rice. In 1979, Prof. Chen Yanxi at the Beijing Agricultural University led a group of scientists working on beneficial rhizosphere bacteria to promote crop growth and disease control. He designated the biological control agent (BCA) as "yield-increasing bacteria (YIB)." In 1987, YIB was commercialized and widely used in China on over 3.3 million ha with 48 different crops (Mei et al 1989).

Beginning in 1989, Chen Zhiyi at the Institute of Plant Protection, Jiangsu Academy of Agricultural Sciences (JUS), in collaboration with IRRI, isolated many antagonistic bacteria from paddy fields. Among the 1274 isolates, some possessed the ability to promote growth of rice plants. Field tests of some of the antagonists indicated that there was no correlation between greenhouse tests and field performance. Using sclerotia of *R. solani* as bait, many new isolates obtained appeared to have higher biocontrol ability. Initial field experiments indicated that sheath blight severity on rice plants treated with B-916 was significantly lower than in check plots where B-916 was not applied. A 1991 trial showed that the control values of strains 3 1-2, 9 1, and 236 were 51%, 45% and 43% respectively. The 1992 trial was repeated with 91, 91 + a fungicide (Jingangmycin), strain 8-14, and Jingangmycin. Results indicated that the control values were 74%, 65%, and 126% against Jingangmycin. Plots receiving P-91 and P-91 + Jingangmycin treatment yielded at least 20% higher than check plots. The results from Jiangsu confirmed the abundance of BCA in paddy rice systems. In vitro, many expressed a strong inhibition effect on fungal pathogen mycelium growth, but did not function well for sheath blight control in field conditions.

The available information therefore shows that rice ecosystems support abundant antagonistic bacteria (Mew and Rosales 1986). Many of them have broad-spectrum activities to suppress the development of more than one disease of rice. Rice seeds also carry a large number of microorganisms—both fungi and bacteria. Surveys show a diversity of microorganisms associated with rice seeds. About 20% of the total bacteria isolated are pathogens whereas 70% are nonpathogenic with no clear functions identified. Another 10% of the bacteria exhibit biological control activity against both fungal and bacterial pathogens based on dual culture tests. These biological control agents can be further classified into three groups based on seed germination tests; some appear to have no effect on seed germination or seedling vigor, some cause a deleterious effect on seed germination, and some promote seed germination and enhance seedling vigor (Rosales and Mew 1997). These microorganisms are a major component of the internal resources in rice ecosystems. They offer potential for disease management, an area that is highly relevant to China where chemical control is often the only option for disease control.

The important question to ask is, What approach should be used with these naturally occurring BCA for disease management? Can we enhance the diversity and population density in rice ecosystems to suppress disease development? In resource management, the key is to minimize external resources but capitalize on internal resources. In rice disease management, using the naturally occurring BCA in the ecosystem for biological control agrees with disease management principles. However, questions remain on whether BCA technology is realistic and whether it is sufficient to achieve disease management. Or, should we rely on a conventional approach through isolation, identification of efficacious strains, and development (mass production and commercialization) and introduction to control the numerous and destructive rice diseases for stable crop production?

Moving from an economic threshold (ET) model to the behavioral decision model

Insect pest management research has been trapped in the ET concept since 1956. Though useful when it was derived to basically minimize insecticide use, the model has developed into mandatory research activities in many national agricultural research systems (NARS). China perhaps has the highest number of threshold research projects going on. The practical reality is that farmer decisions are not based on thresholds or any of these "instruments," but are governed by behavior. In the 1970s there was much literature on decision analysis in agriculture. The concept was that decisions are based on some economic rationale and people (e.g., farmers) would tend to maximize utility (i.e., best benefits) or minimize risks. And all farmers consciously go through a mental calculation of utility before making a decision. Recently, this concept has been challenged and proven wrong. The behavioral decision model is becoming more acceptable. This model developed from psychology basically says that peoples' decisions are based on various aspects such as behavior attitudes (comprising perceived benefits and perceived risks), subjective norm (peer pressure), and perceived control. These elements of the model called the Theory of Planned Action can be measured and this area of research is documented in medicine and health care. Opportunities exist to integrate "decision sciences" into IPM" research, especially on shifting the ET paradigm to the behavioral model.

Opportunities for research impact on rice pest management

Research affects pest management at different scale levels and for different sets of decision-makers in China. While the predominant concern must be for improving decision-making at the farm level, in line with the concept that many pest management activities occur at the field level, phenomena on a wider scale cannot be ignored because of the migration (faunal) or dispersal (floral) potential of different pest types. Thus, in suggesting opportunities for impact, we illustrate these with topics that concern different scale levels.

Opportunities to use biotechnology tools in rice genetic improvement and deployment

Resistance to insect pests

Host plant resistance to insect pests of rice is a research area with a long and successful history both in China and at IRRI. Almost all rice varieties released over the past 20 years have had resistance to multiple insect pests (Khush 1989). This resistance serves as an important complement to biological control by natural enemies and, when required, insecticide application. Any innovative and widely applied pest management methodology, such as insect host plant resistance, must continue to evolve as lessons are learned from past experience and new approaches become available through scientific advances. We will briefly review aspects of insect host plant resistance in rice that require improvement, and new opportunities to address these problems.

The brown planthopper, *Nilaparvata lugens,* was the first insect pest of rice for which highly resistant varieties were developed. These varieties played an important role in suppressing BPH outbreaks that resulted from the overuse of broad-spectrum insecticides, which severely disrupted biological control. However, when cultivar resistance broke down, which in some cases happened in as little as 2 years after the introduction of a new resistance gene, the BPH outbreaks resumed (Gallagher et al 1994). In the tropics, it is clear that BPH outbreaks are the symptom of a disease, not the disease itself, which is insecticide overuse. Extensive experience has now demonstrated that when insecticide use is kept to a minimum, BPH outbreaks in tropical areas are rare (Gallagher et al 1994). In contrast, in temperate areas such as central China, outbreaks of BPH and the whitebacked planthopper, *Sogatella furcifera,* frequently result from mass migration of planthoppers from tropical areas (Perfect and Cook 1994). These migrations often occur early in the season, before the buildup of natural enemy populations.

Insecticide use has decreased over the past decade, partly as a result of integrated pest management training, but there is a continuing need for BPH-resistant varieties in both tropical and temperate areas. In the tropics, host plant resistance provides "insurance" against BPH outbreaks that may result from insecticide overuse or unusual weather patterns. In temperate areas, resistant varieties are an essential defense against large planthopper immigrations. Our current challenge is to develop cultivars with more durable resistance. There is a need for alternatives to single major gene resistance, which is prone to breakdown. One promising approach is to use complexes of minor genes, a strategy that has been more extensively used for management of plant pathogens. Breeding varieties with polygenic, minor gene resistance is more difficult than using major genes, but should become more practical with the development of molecular markers for "quantitative trait locus" (QTL) analysis. We have just completed the first QTL analysis of BPH resistance, and determined that a complex of minor genes accounts for the observed durability in the field of the popular cultivar IR64 (Alam and Cohen 1998).

In contrast to breeding for planthopper resistance, where major genes have generally been used, breeding for stem borer resistance has relied on minor genes (Chaudhary et a1 1984). This is principally because, despite screening thousands of traditional rice varieties, no source of major genes for stem borer resistance has been discovered. Most improved semidwarf varieties have a moderate, and apparently durable, level of stem borer resistance. This moderate resistance is often underappreciated by rice scientists and farmers, because stem borer damage still occurs in the field, but it is in fact a significant component of stem borer management in rice.

Nonetheless, further increases in the level of stem borer resistance can increase rice yields. An approach that is currently receiving a great deal of attention is the use of insecticidal genes from the bacterium *Bacillus thuringiensis* (Bt), which can be introduced into plants via genetic engineering. Bt rice plants have been produced by more than 20 research groups including some in China (Wu et al 1996) and at IRRI (Ghareyazie et al 1997). However, none of these lines have yet been field tested, and several advances remain to be made. A major challenge in using Bt rice will be to slow the evolution of stem borer adaptation to Bt toxins. As with any insecticide, insects will rapidly develop resistance to Bt toxins unless the toxins are used wisely (Tabashnik 1994). Collaboration between entomologists and plant molecular biologists is essential in the design and evaluation of Bt rice varieties (Cohen et al 1996). A workshop to foster such collaboration was held at IRRI in November 1997, and two research groups from China participated.

Cloning of disease resistance genes

Successful cloning of plant disease resistance genes represents a major milestone in plant science research and is expected to have significant impact on crop protection. Since 1993, over 20 disease resistance genes against diverse groups of pathogens have been cloned from different plant species (see review by Baker et a1 1997). In rice, two resistance genes, *Xa1* and *Xa21,* conferring bacterial blight resistance, have been cloned (Song et a1 1995, Yoshimura et al 1997). Remarkably, all resistance genes cloned so far encode one or more conserved motifs such as leucine-rich repeats (LRR), nucleotide binding sites (NBS), and kinases. For instance, *Xa21* encodes a protein containing LRR and kinase motifs, whereas *Xa1* encodes a product with LRR and NBS.

Two immediate applications for crop improvement can be derived from this discovery. First, using the conserved sequences of cloned resistance genes, resistance genes or their analogs (genes with structural similarity to functional resistance genes) can be isolated by PCR techniques (reviewed by Michelmore 1996). The cloned resistance gene analogs can then be mapped to chromosomes to confirm the function. Thus, there is enormous potential for accumulating these cloned resistance genes using a transgenic approach. The second application is to use resistance gene analogs as molecular markers to identify germplasm with diverse resistance in a breeding program. This approach has the advantage of using markers that directly correspond to the functional genes, hence overcoming the problem of recombination between linked markers and target genes in marker-aided selection. Improved efficiency in marker-aided breeding will promote the identification and use of more diverse resistance sources.

Expanding the rice gene pool through plant genomics research

Rapid progress in genome sequencing in rice and other plant species will provide an enormous database for the identification of genes involved in plant defense. The discovery that arrangements of genetic and DNA markers on chromosomes of major cereals (rice, barley, wheat, rye, and maize) are similar has made the gene pool in other cereals accessible for rice improvement. Both advances will lead to trait discovery.

Understanding pathogen evolution

Years of basic research on pathogen genetics has led to the development of genetic systems that allow for efficient cloning of genes involved in pathogenesis. A variety of molecular markers are now available for tracking the evolution of pathogens in the field. Availability of near-isogenic lines containing single resistance genes also permits the assessment of quality of resistance genes against pathogen populations over a broad geographical region. These tools together allow us to develop a gene deployment strategy based on complementary information about host resistance and virulence characteristics of pathogen populations.

Research needs

Three strategic steps can be considered in the development of complementary technologies for disease management:

- Diversify resistance sources. The number of resistance genes currently used in cultivars is relatively small compared to the total germplasm pools available for use. With greater efficiency in gene identification and cloning, it is possible to extract diverse and effective resistance genes from the expanding gene pool. This approach will lead to greater functional diversity among cultivars and provide the "components" needed to manage disease at the population level (e.g., use of multilines and cultivar mixture).
- Develop broad-spectrum resistance. The availability of highly saturated molecular maps of rice makes it possible to locate and determine the effects of quantitative loci for disease resistance. With marker-aided selection for quantitative resistance, we can remove the long-standing constraint of accumulating both pathotype-specific and nonspecific resistance in cultivars. This approach will be particularly important in addressing the blast problem where the pathogen can evolve rapidly to overcome major resistance genes.
- Assess resistance genes proactively. We should aim at generating knowledge to proactively assess the quality of resistance genes. Since the durability of a resistance gene is in large part a manifestation of the adaptability of the pathogen, it is possible to assess the genetic load of adaptation as an indirect measure of the durability of specific resistance genes. Tools are now available to track the evolution of a pathogen at the molecular and phenotypic levels. Systematic evaluation of fitness changes in pathogen population as influenced by resistant cultivars will add to this basic knowledge.

Each of these component technologies requires strong disciplinary research. While each component on its own is unlikely to solve all disease problems, the combined knowledge and elite germplasm generated form a basis for an integrated disease management program.

Opportunities to increase implementation of biological and natural control on rice diseases

While there is progress in biological control in both research and application, two issues hinder the advance of biological control as a viable disease management technology: one relates to the very nature of BCA in disease management and the other is on scaling-up of the biological control technology.

1. Inconsistency of field performance with BCA for rice disease management

This phenomenon is comparable to many other findings using microbial antagonists for biological control of other crop diseases. It has raised concerns about whether biological control is indeed a viable option for rice disease management. This problem is well recognized and some suggested that the "inoculum" of biological agents is ecologically unsuited to the environments where they must operate (Deancor 1983). To overcome this we must design more appropriate screening strategies.

Basically, however, there has been a perception problem of equating biological control with chemical control (Mew et al 1993). This perception has made the application of BCA in disease management less dependable and short-term. Microorganisms intended for use as biocontrol agents must be considered in a biological paradigm and not the current chemical paradigm. “To treat introduced microorganisms in a chemical rather than a biological paradigm is an unrealistic expectation” (Cook 1993). Microbial biocontrol is often crop- and site-specific. We believe that there is an ecological advantage in pursuing our research on the indigenous microbial biological control agents. The real potential for microbial biocontrol of plant diseases may well be in the use of many different locally adapted strains for different diseases in different sites (Cook 1993). As the rice ecosystems are rich in microbial biocontrol agents, it may not be necessary to introduce alien strains from unrelated ecosystems. The question is how to manage or enhance the naturally occumng microbial antagonists in the rice ecosystems.

While the initial stage of the work on biological control of rice diseases is promising, conceptually, however, biological control agents are applied and treated in the same manner as fungicides. In a few strains we tested, the biological property neither can be, nor should be, compared favorably with the chemical property of fungicides used against the same diseases. Consequently, the full potential of microbial biocontrol in rice disease management is addressing the “immediate effect” rather than the “long-term” impact of biological control in field evaluation.

2. Time needed to readjust the BCA population in rice canopy

The BCA population declines to an undetectable level within 24 to 48 hours after initial introduction. Even though the BCA originates from the paddy, they are saprophytes and there are other microbes in the systems. There will be equilibrium of the microbes in the phyllosphere. There is competition for nutrients and sites. The introduced BCA must be very competitive or must occupy a specific niche. Conventionally, BCA is applied as a protective rather than as a curative measure. But if it is introduced at the right time with an effective dosage, BCA can be more effective as a curative. To maintain an effective dosage, inevitably microbial biocontrol agents need to be introduced more frequently. This, however, is impractical and uneconomical. Research should lead in identifying ways that sustain microbial biocontrol agents applied into the canopy.

IRRI has examined this issue for the last several years. The most encouraging finding was that BCA can be isolated from both healthy tissues as well as disease lesions such as blast and sheath blight (Mew et al 1993). There are times when more BCA is isolated from lesions than in healthy tissues. BCA should be deployed therefore in relation to a rice disease epidemic process rather than as a preventive measure to protect the crop. The preventive measure works only if we maintain an effective dosage all the time.

The functional relationship of BCA to a rice disease pathogen such as *Rhizoctonia solani* AG 1 is to reduce the number of disease foci, “lesion expansion,” “focal point expansion,” “infection efficiency,” or “inoculum efficiency,” and thus reduce the secondary spread of a disease. The initial lesion development of a disease may be essential to provide “refuge” or a “supporting system” to maintain that “effective dosage” of BCA on the rice plant surface. Or BCA is mixed with a fungicide (at a lower dosage) to provide a “window” of protection before BCA is activated for action in the canopy. Ideally therefore, BCA should be deployed when a plant disease begins to develop in the field. In Jiangsu, China, BCA strain 916 was introduced with a high inoculum density at maximum tillering or early booting stage when sheath blight lesions have initially developed (based on historical data of disease occurrence survey). The results were encouraging.

3. BCA for long-term sustainable disease management

In the Department of Agriculture in Thailand, research was conducted to evaluate the relationship between BCA application and foci of sheath blight in farmers' fields (Nongrat Nilpanit and Parkpian Arunyanart, personal communication). When BCA mixture was applied every crop season to a farmer's field known historically to have high incidence of sheath blight, sheath blight foci decreased from 77% in the first crop to 20% in the fifth crop cycle, while in neighboring fields it remained very high. Application of BCA appeared to sustain sheath blight management in farmers' fields.

In Jiangsu, China, the long-term effect of strain B-916 applied for the past 3 years in thousands of hectares indicated that sheath blight decreased in some fields in a particular site; full experiments are in progress to assess sustainable disease management with BCA.

In the context of sustainable disease management, the question of what BCA can offer that chemical fungicide cannot needs to be addressed. The advantage of BCA is that they are part of the internal resources of an ecosystem. The activity of a BCA product may not be as high as a fungicide, but it may offer "cleaner and greener" options or options of sustainability. BCA should not be seen or treated like a fungicide. It cannot and should not be targeted to replace fungicides. We may not need to have a "stand-alone" BCA product, because BCA can be complementary to some of the fungicides, especially to reduce the frequency and dose of application of a widely used fungicide.

4. Other factors that limit biological control technology

In China alone there is much research on biological control of plant diseases, but not many BCA are commercialized, although the number is large when compared with other countries. There are limiting factors:

- Research is often dissociated from end-users. There is no clear mechanism in place to link research to extension.
- Registration of a BCA product is costly and tedious. It is both costly to generate data for registration and the process is quite long. In general, the data requirement of microbial biocontrol agents should be different from biochemical-based pest control agents, e.g., antibiotics, even though the bases of BCA are secondary metabolites or antibiotics. Definitely BCA should not be treated like a fungicide in registration requirement.
- Stability of BCA products is difficult to maintain. There are problems in methods of analysis and quality control. Research on BCA deployment as internal resources is needed.
- Ease of handling of a product by the end-user is as important for a biological one as it is for a chemical one.
- Storage and shelf life are another major handicap of BCA products. We should search for other options for BCA application.

Approach

1. Design screening strategy to isolate and identify efficacious BCA strains.

The current method based on in vitro screening may not be adequate but is the most commonly used method to screen BCA against target pathogens. It is equally important to target the control value or determine the level of disease control where the introduction of BCA is most efficient so that an effective dosage is established.

The challenge is using one microorganism (BCA) to control another microorganism (the disease pathogen). When BCA is introduced into the crop production system, the disease declines very fast. We should consider BCA screening and development in terms of plant breeding: new varieties with new traits or better performance are developed every year, so identification of new or monitoring of improved performance of old strains (genotypes) should be done routinely. The targets of screening for new strains against disease epidemic components or against more pathogens should also be set. It is recommended that BCA strains be screened for proven new secondary metabolites or antibiotics.

In using BCA, we have to recognize that the BCA is a living barrier to the pathogen (competition for site and space), that BCA is a sink for nutrients needed by the pathogen (competition for C and N), and that BCA is a delivery system for natural inhibitors (antibiotics or other secondary metabolites).

2. A delivery system of BCA—the Jiangsu model in China

For a biological control technology to have an impact, there is a need to identify extension mechanisms to link farmers or end-users in BCA development, formulation, and production. Based on the large-scale testing of B-916 for sheath blight control in Jiangsu, the inoculum B-916 was prepared in response to the demand from farmers—the number of fields and the total area needed. The Institute of Plant Protection of JAAS in collaboration with the Microbial Fermentation Plant, Nanjing Agricultural University, produced the amount needed for that year. In 1997, the total volume of B-916 fermented product (in liquid form) was 10 t. The demand in 1998 just for one site was 16 t. Salient features of the Jiangsu production system are:

- With this production system, the Institute of Plant Protection maintains the original cultures of B-916 in freeze-dried form, guides the quality control of the product, and also sets the standard.
- This production system provides an ideal way of "supplying local production (supply side) with local strains of BCA for local use (demand side)."
- It may be feasible that a production unit established or affiliated with the Institute of Plant Protection, or an affiliated Biological Control Center, produce the BCA and also assure the quality control in response to demand of local plant protection stations across the province.
- In this way, production responds to the demands of farmers for the year, thus avoiding issues of "shelf life" and "storage" of BCA.
- This system may also be applicable to other countries in Southeast Asia.
- The shortcoming of this system is that there may not be a big profit in the commercialization of BCA.
- It targets the "local market" only and BCA should be considered as an "inoculant" (the Japanese approach) instead of a "microbial fungicide."

Further research needs to be conducted to extrapolate this model to other parts of China and to determine what modifications are required to make BCA technology more location-specific.

Opportunities to use biodiversity for pest management at farm and landscape levels

There has been an increased awareness by rice scientists that rice fields must be considered in totality as ecosystems, and that pest management inputs that do not disrupt the fine balance that exists in these human-managed agricultural systems must be identified. This awareness has led to substantive application of ecological concepts to pest management, in which there is an explicit recognition of the importance of natural enemies of insect pests and antagonists of plant diseases in keeping pest populations below damaging levels. This awareness may be translated simplistically into the concept of introducing or maintaining an acceptable level of diversity in rice ecosystems determined through research at different scale levels (field, farm, community, landscape) and across scale levels. Such research puts into practice potentially useful tools and strategies to manage biodiversity in rice ecosystems for purposes such as pest management.

The term biodiversity is defined in this paper as the diversity that exists in rice-based ecosystems at the species, genetic, and habitat levels. Species diversity refers to the cultivar of rice pests, and their natural enemies, including parasites, pathogens, and predators of insect pests, pathogens, and herbivores of weeds, and microorganisms antagonistic to rice pathogens and weeds, linked together by natural phenomena such as "food chains" to give functional relationships between species of different trophic levels. Genetic diversity includes the diversity of rice germplasm and of commercial cultivars used by farmers, the variation that may exist within cultivars in their pest resistance properties, and the corresponding diversity that exists in pest populations in their abilities to infest the same or different rice cultivars. *Habitat diversity* includes the variation of microclimate and habitat within rice fields, as well as the plant communities surrounding rice fields. The conservation and manipulation of biodiversity within and around rice fields can be used to develop sustainable, low-cost, and environmentally compatible crop protection technology for wide dissemination among the poor.

Knowledge of the *genetic diversity* of a rice-pest system can serve as a basis for managing pest populations by deploying host plant resistance. A spectrum of strategies can be considered for increasing crop genetic diversity (Fig. 1).

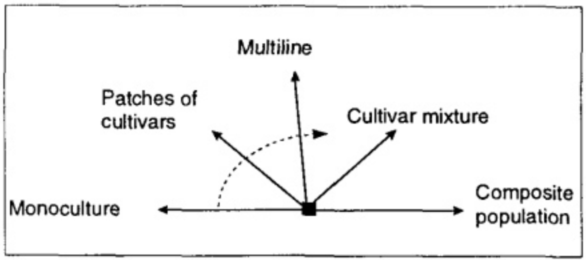


Fig. 1. The range of strategies by which the diversity of crop varieties can be developed.

Different crop genotypes can be utilized over time; a patchwork of pure lines can be cultivated at a given time; cultivars or lines can be mixed; and composite populations can be produced. Which of these diversification strategies is most effective and acceptable will depend on the biology and ecology of the pest, and on particular conditions under which the crop is grown. These different uses of host population diversity can reduce disease and insect damage and increase the useful lifetime of resistance genes. Although it is clear that the widespread cultivation of uniform crop genotypes leads to instability of production, little work has been done to develop or assess methods for employing greater crop biodiversity for rice. Agricultural intensification has in general led to decreases in cultivar diversity. Factors that decrease environmental diversity and reduce farmers' overall risk tend to lead to decreases in cultivar diversity. This trend, which has distressed those concerned about the erosion of crop genetic resources, is not inevitable. If scientists and farmers are aware of the importance of maintaining cultivar diversity for pest and disease management, and see attractive mechanisms for increasing cultivar diversity without loss of productivity and income, it should be possible to maintain or increase cultivar diversity in spite of agricultural intensification.

Knowledge on habitat diversity will help determine if nonrice habitats interspersed among rice fields improve the effectiveness and continuity of naturally occurring biological control of insect pests. Our challenge is to determine whether nonrice habitats are in fact useful, and, if so, which types of nonrice habitats and which spatial patterns of habitats are best. Should forested areas containing shrubs, banana, and coconut trees be preserved? Or do grassy bunds between fields provide sufficient refuges for important natural enemies? If forested areas are important, how close to rice fields should they be, and what is their minimal effective size? While it will be difficult to develop definitive answers to these questions, so little is now known about them that initial research efforts should yield much valuable information.

The physical environment of rice ecosystems — topography,landscape, soil types, climate—directly and indirectly influences the biodiversity in any area, in addition to the influence of agricultural practices. All living organisms have preferred conditions for their growth and development, and, within an area, the biodiversity reflects these conditions. The population dynamics of any species is also strongly influenced by its prevailing environment in the form of short-term weather and availability of a host, in the case of parasites. The quantitative relationships between environmental factors such as weather, soil type, agronomic practices, etc., and the population dynamics of key pests have not been extensively researched in China, even though specific models have been developed for blast and sheath blight that predict the likelihood of the disease developing into epidemic levels. At IRRI, the influence of crop intensification factors such as increased nitrogen fertilization and closer plant spacing has also been quantified for key diseases. Geographic information systems (GIS) software for the spatial characterization of pest occurrences has been used for blast and brown planthopper, while work is ongoing to apply GIS techniques for linking soil and topography to pest outbreak zones. This epidemiological knowledge on pest population dynamics will serve as a basis for integrating background information on habitat and genetic diversity, and provide predictions on the likelihood of outbreaks from the deployment strategies developed.

Fully using biodiversity for sustainable pest management will require that a systems approach be adopted, in which there is integration of interdisciplinary knowledge available for an area. Thus, it may be foreseen that area-based pest management strategies will be practiced in which habitats are manipulated using knowledge on genetic and species diversity, and the influence that the physical environment exerts on them. To make these fully sustainable will finally require that the strategies be matched to the needs of the human communities in these areas in the context of a landscape.

In China, as in other countries, agriculture "geometricizes" the land by replacing nature's soft curves and habitat heterogeneity with hard, straight, and uniform lines of mechanization. Such landscape reshaping, when combined with other farmer practices (e.g., plowing, harrowing, pesticide applications), brings additional consequences for altering biocontrol linkages in the rice ecosystem. Indeed, as natural landscapes have given over to agriculture, loss of habitat structure (in size, shape, orientation, number, or arrangement) has come to mean loss of biodiversity (in real or imagined terms). Understanding spatial features across agricultural landscapes is fundamental to determining how different farmer practices affect disease, insect, and weed population structure, pest-natural enemy dynamics, crop damage, and yield. Because plant protection specialists (entomologists, plant pathologists, weed scientists) have tended to focus on individual crop patches (single or multiple fields), interactions and exchanges across the larger landscape that includes hedgerows, forest patches, and human settlements, as well as crop patches, have largely been ignored.

The guiding principles for conserving, enhancing, and sustaining biocontrol strategies through landscape modification are systematized in the new disciplines of landscape ecology and conservation biology. Landscape ecology emphasizes the study of interactions and exchanges across boundaries within heterogeneous landscapes, effects of spatial heterogeneity on biotic and abiotic processes, and strategies for managing and enhancing spatial heterogeneity. Landscape ecologists have shown, for example, that landscapes exhibit repeated patterns in urban, agricultural, and natural ecosystems, and that landscape boundaries exert significant filter effects on energy, nutrients, and biodiversity across local, regional, and global scales. The goals of conservation biology are to conserve biodiversity, natural ecosystems, and biological processes to better understand idiosyncrasies of ecological systems. Conservation biologists have shown, for example, that corridors of natural vegetation provide population refuges and optional routes for species movements, and play key roles as conduits and barriers in controlling wind and soil erosion.

Recent research in Asia has shown that levees (=bunds) are vital refugia for some early-season predators (i.e., spiders and ants) that are incapable of long-distance dispersal, while certain bordering grasses (i.e., *Paspalum* spp.) support large populations of crickets (e.g., *Anaxipha longipennis, Metioche vittaticillis*) that are efficient predators of rice leaffolder eggs. In addition, studies of rice food-webs in different, widely separated sites in the Philippines revealed observable differences in arthropod abundance, but not species composition, arthropod phenology, and web structure when distances between sites were as large as the dispersal distances of the more mobile rice-associated species. Given this information, we would not expect closely spaced samples taken at a single site to show appreciable differences in food-web structure from one part of the field to another. An open question, however, is how individual pest and natural enemy species distribute themselves within and across connected (bunded) rice fields and which habitats serve as sources and sinks for such species. Identifying, testing, and deploying promising spatial features of rice landscapes for enhanced biological control is a natural next step in rice landscape research.

Some practical questions for future research of rice landscapes in China include:

1. What role(s) do rice bunds and bordering vegetation play as sinks and sources for pest and natural enemy populations during growing and fallow seasons?
2. What patterns of spatial distributions do pest and natural enemy populations show in abundance within rice fields and between rice fields and nonrice habitats?
3. Do weeds function as natural enemy refuges and, if so, is selective weeding a management option?
4. What effect, if any, does field shape have on rice yields and biodiversity relationships?
5. How do invertebrate communities respond to rice-nonrice boundaries as the landscape becomes further fragmented?

Cognizant of the need to research modes for disseminating knowledge-based technologies, such as those on gene deployment and habitat manipulation, IRRI scientists have involved farmers and extension services in participatory experiments in several NARS. This experience will be used to design similar participatory experiments at two “lighthouse” sites in China (Yunnan Plateau and Yangtze Delta) as part of a recently implemented project called “Exploiting biodiversity for sustainable pest management.”

Opportunities to increase information delivery to farmers

China has an extensive network of agricultural research and extension workers, within which national and provincial needs are juxtaposed. It is within this network that new approaches to pest management will have to operate in the short term. Apart from the. production and dissemination of seeds of improved rice cultivars, Asian agricultural research and extension networks commonly have to disseminate knowledge on crop, resource, and pest management. Increasingly, scientists are realizing that the processes for disseminating seed-based technologies are different from those for knowledge-based technologies.

Types of knowledge

Knowledge-based or knowledge-intensive technologies (KITs) are those which allow farmers or others to make informed decisions about the use of an input for rice production (such as seed, fertilizer, water, or pesticide) or about a situation. Examples are (a) diagnostic kits to detect disease before symptoms are visible and therefore ensure needed applications of fungicides, and (b) decision-support tools or expert systems that have been used in industrialized economies to guide fanners in their pest management strategies. In rice pest management, the “no early spray against leaffolders” is an example of a simple rule which is a KIT. Pest management, in particular disease management, has been relatively successful in avoiding severe epidemics through the use of improved seed, which represents a physical technology. This has been touted as the major accomplishment of many national and international agricultural research systems (Teng, Fischer, and Hossain 1995); yet its use has also been criticized due to the unpredictable durability of disease resistance genes unless the seed is used with concomitant knowledge of its environment and how that affects the rate at which pathogen populations may evolve to overcome the resistance. Thus, knowledge on deployment of resistance according to the physical environment in the form of strategies also represents another form of KIT. There are, as yet, few operational KITs in China for key pests, and the development and evaluation of these could be a prime target for collaborative research.

Use of communication techniques and information technology

Because KITs depend on farmers to make timely decisions after assessing their farming environment, it is important that large numbers of farmers learn the rules required to make such decisions. Different modalities have been evaluated for their effectiveness and efficiency in communicating KITs to large numbers of farmers, e.g., farmer participatory research, farmer field schools, and multimedia extension campaigns. It is as yet unclear which of these are most suited to a particular set of farmers characterized by the set's attributes such as age, education, and farming skills. What is further unclear is the role of information technology (computers, networks, etc.) in conveying information to assist provincial decision-makers in China. Because China has a big network of human resources for pest management, the potential for information technology may be high if rice agriculture changes towards systems of less labor and larger farms.

Redefining the institutional support system for pest management at different scales

Pest management decisions are decisions made under uncertainty. When such decisions are made, people often use decision rules (Eiser 1986, Payne et al 1992). The term "heuristic" was introduced by Kahneman and Tversky (1973) to refer to an informal rule-of-thumb used to simplify information processing and decision-making. Heuristics are developed through experience about possible outcomes and may have inherent faults and biases (Slovic et a1 1977). Farmers' reaction to pest and disease damages by using sprays may well be due to faults in their beliefs or the heuristics they use (Bentley 1989). Research to understand the existing decision rules that farmers use to manage particular pests or symptoms is essential in determining the types or framing of information intervention. This area of research often provides social scientists and biological scientists opportunities to collaborate.

In a recent experiment to change farmers' perceptions on leaf-feeding insects, Heong and Escalada (1997) applied the cognitive dissonance theory (Festinger 1957) to motivate farmers to evaluate a conflict information expressed as a heuristic—"Insecticide application in the first 30 days after transplanting (or 40 days after sowing) for leaffolder control is not necessary." Participating farmers, after their evaluation of the heuristic, significantly changed their perceptions and reduced insecticide use. Similar farmer participatory experiments conducted in Vietnam had the same effects on perceptions and practices of farmers (Heong et a1 1995).

While successes in the use of farmer field schools are well demonstrated by the Food and Agriculture Organization (FAO) IPM program in Indonesia and Vietnam, the training had reached only 5% of rice farmers in these countries after 9 years. There are perhaps more than 80 million rice farmers in China and reaching them with pest management information that can reduce their pesticide use is an enormous task. Researchers have opportunities to investigate the use of mass media. In Vietnam, an experiment was carried out recently to evaluate the use of media to encourage farmers to stop early-season insecticide use. Through the use of radio, leaflets, and posters, the message reached 97% of the targeted 20,000 households in Long An province. Farmers in the area reduced their insecticide sprays from 3.8 to 1.6 per season 16 months after the campaign was launched. The proportion of farmers who believed that the leaffolder was damaging and required spraying dropped significantly from 60% to 20%. About 90% of the farmers cited savings in insecticide costs and labor as their main incentives in stopping early-season spraying.

In China, many provinces still maintain village-level broadcasting systems. At the moment, messages from such systems are targeted at warning farmers and inevitably encouraging them to use pesticides. These are potential systems in which changes in message content towards a more rational pesticide use may be evaluated. In this regard, there are many areas for multidisciplinary research to look at the effects of communication methods on farmer perceptions and decision-making behavior, including the use of different approaches and message-framing techniques.

Conclusions: a framework for China-IRRI collaboration

Rice is the preferred staple food of China as well as of Asia. Because of China's population, food security in China is strongly linked to food security in Asia. More than 90% of the world's rice is produced and consumed in the region, where the human population is estimated to increase by about 80-100 million a year. In 1996, only about 15 million t were available for trade by five Asian countries. Any factor that disrupts the rice supply for trade significantly raises the world rice price because of the importance rice has in the social fabric of this continent. FAO estimates that rice supply in Asia must increase by 3.5% per year to prevent an increase in malnutrition. As the average growth rate of rice production over the past two decades has been roughly 2.5% per year, achievement of this target will require concerted efforts between partners, a sound vision of the future, and good luck.

Rice research has undoubtedly brought significant gains in production over the past 30 years in China. Most of these gains came from the introduction of improved rice varieties and were amplified by improved irrigation. Today, with continued population growth and evidence of declining irrigated land area, strategies for increasing production are much more complex than they were 20 years ago. Therefore, research efforts have to be concentrated not only on the biophysical aspects of production–crop improvement, cultural practices, reducing preharvest and postharvest losses, reducing environmental externalities of misuse of chemicals, seeking more efficient ways of fertilizing the crop — but also on the socioeconomic aspects, including institutional and policy. It is in this context of increasing production and productivity yet sustaining or even improving the natural resource base with appropriate technologies and policies to ensure a sustainable rice system that a relatively new approach called the ecoregional approach is particularly relevant (Teng, Hossain, and Fischer 1995). This approach proposes that natural resource management — which includes many aspects of pest management such as biodiversity, conservation, impact of pesticides on land and water quality — should be done within defined geographic areas called ecoregions, and that issues related to pest management should not be treated in isolation from other issues of natural resource management such as fertilizer and soil management. Ecoregions are therefore one or more contiguous areas with related agroecological attributes; the Yunnan Plateau may be considered a small ecoregion with several distinctive subregions. Indeed, the ecoregional approach captures the Chinese way of looking at natural systems, in which natural balances so vital to maintaining stability and interaction between the owners of the natural systems are recognized. To focus IRRI-China efforts in collaboration, it is proposed that an ecoregional approach based on rice production systems in different geographic regions of China be used (Annex 1) in which key pest management issues are identified, researchable topics specified, and both national as well as provincial institutions have clear contributions in identifying resolution of the issues.

China faces some clear challenges in its efforts to increase rice production, among which improved pest management is one. What is equally clear is that the efforts of Chinese scientists can be greatly enhanced by collaborative research with IRRI scientists if there are common research targets and objectives. This paper has presented some of the topics which are researchable and, if successful, could contribute to the overall goal of more rice in a safe environment. The meeting in which this paper has been presented is therefore an important first step towards building a partnership that will take us into the next millennium.

References

Alam SN, Cohen MB. 1998. Detection and analysis of QTLs for resistance to the brown planthopper, *Nilaparvata lugens,* in a doubled-haploid rice population. Theor. Appl. Genet. 97(8):1370-1379.

Baker B, Zambryski P, Stakawicz B, Dinesh-Kumar SP. 1997. Signaling in plant microbe interactions. Science 276:726-732.

Bell SS, McCoy ED, Muschinsky HR, editors. 1991. Habitat structure. The physical arrangement of objects in space. Chapman and Hall.

Bentley JW. 1989. What farmers don't know can't help them: the strengths and weaknesses of indigenous technical knowledge in Honduras. Agric. Human Values 6:25-31.

Blakeman JP. 1985. Ecological success of leaf surface microorganisms in relation to biological control. In: Windels CE, Lindow SE, editors. Biological control in the Phylloplane. St. Paul: APS Press. p 6-30.

Chaudhary RC, Khush GS, Heinrichs EA. 1984. Cultivar resistance to rice stem borers in Asia. Insect science and its application. 5: 447-463.

Cohen MB, Aguda RM, Romena AM, Roderick GK, Gould FL. 1996. Resistance management strategies for Bt rice: what have we learned so far? In: Rice genetics III. Proceedings of the Third International Rice Genetics Symposium, 16-20 October 1995. IRRI.

Cook RJ. 1993. Making greater use of introduced microorganisms for biological control of plant pathogens. Annu. Rev. Phytopathol. 31 53-80.

Cramer HH. 1967. Plant protection and world crop production. Pflanzenschutz Nachrichten 20(1). 524 p.

Deancon JW. 1983. Microbial control of plant pests and diseases. New York: ASM Series. 70 p.

De Kraker J. 1996. The potential of natural enemies to suppress rice leaf folder populations. PhD thesis. Wageningen Agricultural University, Netherlands.

Eiser JR. 1986. Social psychology: attitudes, cognition and social behaviour. Cambridge University Press.

Evenson RE, Herdt RW, Hossain M. 1996. Rice research in Asia: progress and priorities. IRRVCABI. 418 p.

Fabellar LT, Fabellar N, Heong KL. 1994. Simulating rice leaf folder feeding effects on yield using MACROS. Int. Rice Res. Newsl. 1917-8.

Festinger L. 1957. A theory of cognitive dissonance. Stanford University Press.

Forman RTT. 1995. Land mosaics. The ecology of landscapes and regions. Cambridge University Press.

Gallagher KD, Kenmore PE, Sogawa K. 1994. Judicial use of insecticides deter planthopper outbreaks and extend the life of resistant varieties in Southeast Asian rice. In: Denno FW, Perfect TJ, editors. Planthoppers: their ecology and management. New York: Chapman and Hall. p 599-614.

Ghareyazie B, Alinia F, Menguito CA, Rubia LG, de Palma JM, Liwanag EA, Cohen MB, Khush GS, Bennett J. 1997. Enhanced resistance to two stem borers in aromatic rice containing a synthetic *cryIAb* gene. Mol. Breed. 3:401-414.

Gou Y. 1990. Larval parasitization of rice leaf folders (Lepidoptera: Pyralidae) under field and laboratory conditions. PhD thesis. University of the Philippines Los Baños.

Heong KL, Escalada MM. 1997. Perception change in rice pest management: a case study of farmers' evaluation of conflict information. J. Applied Commun. 81(2):3-17.

Heong KL, Schoenly KG. 1997. Impact of insecticides on pest-natural enemy communities in tropical rice ecosystems. In: Haskell PT, editor. Ecotoxicology: pesticides and beneficial organisms. London: Chapman and Hall (in press).

Heong KL, Escalada MM, Lazaro AA. 1995. Misuse of pesticides among rice farmers in Leyte, Philippines. In: Pingali PL, Roger PA, editors. Impact of pesticides on farmers' health and the rice environment. California: Kluwer Press. p 97-108.

Heong KL, Teng PS, Moody KM. 1995. Managing rice pests with less chemicals. Geojournal35(3):337-350.

Heong KL, Thu Cuc NT, Bunh N, Fujisaka S, Bottrell DG. 1995. Reducing early season insecticide applications through farmers' experiments in Vietnam. In: Denning GL, Xuan VT, editors. Vietnam and IRRI: a partnership in rice research. IRRI and Ministry of Agriculture and Food Industry, Hanoi, Vietnam. p 217-222.

Kahneman D, Tversky A. 1973. On psychology of prediction. Psychol. Rev. 80:237-251.

Khush GS. 1989. Multiple disease and insect resistance for increased yield stability in rice. In: Progress in irrigated rice research. Los Baños, Philippines: IRRI. p 79-92.

Mai V, Huan NH, Heong KL, Escalada MM, Lazaro AA. 1997. Pest management perceptions and practices of rice farmers in Long An province, Vietnam. In: Heong KL, Escalada MM, editors. Pest management of rice farmers in Asia. Los Baños, Philippines: IRRI. p 213-225.

McIntosh RA. 1992. Preemptive breeding to control wheat rusts. Euphytica 63:103-113.

Meenakanit L, Vongsaroj P. 1997. Farmers' perceptions and practices in weed management in Thailand. In: Heong KL, Escalada MM, editors. Pest management of rice farmers in Asia. Los Baños, Philippines: IRRI. p 185-199.

Mei Reuhong et al. 1989. Yield increasing bacteria. Beijing: Agricultural Press. 128 p.

Meffe GK, Carroll GR. 1997. Principles of conservation biology, 2nd ed. Sinauer Press.

Mew TW, Rosales AM, Maningas GV. 1993. Biological control of Rhizoctonia sheath blight and blast of rice. In: MH Ryder, PM Stephens, GD Bowen. Improving plant productivity with rhizosphere bacteria. Australia: CSIRO. p 9-13.

Mew TW, Rosales AM. 1986. Bacterization of rice plants for control of sheath blight caused by *Rhizoctonia solani.* Plant Dis. 76:1260-1264.

Michelmore RW. 1996. Flood warning: resistance genes unleashed. Nature Genet. 14:376-378.

Moody K, Escalada MM, Heong KL. 1997. Weed management practices of rice farmers in Iloilo, Philippines. In: Heong KL, Escalada MM, editors. Pest management of rice farmers in Asia. Los Baños, Philippines: IRRI. p 143-160.

Payne JW, Bettmanm JR, Johnson EJ. 1992. Behavioral decision research: a constructive processing perspective. Annu. Rev. Psychol. 43:87-131.

Perfect TJ, Cook AG. 1994. Rice planthopper dynamics: a comparison between temperate and tropical regions. In: Denno RF, Perfect TJ, editors. Planthoppers: their ecology and management. New York: Chapman and Hall. p 282-301.

Rola AC, Pingali PL. 1993. Pesticides, rice productivity and farmers' health: an economic assessment. Los Baños, Philippines: IRRI.

Rosales AM, Mew TW. 1997. Suppression of *Fusarium moniliforme* in rice by rice-associated antagonistic bacteria. Plant Dis. 81:149-52.

Rosales AM, Thomashow L, Cook RJ, Mew TW. 1995. Isolation and identification of antifungal metabolites produced by rice-associated antagonistic *Pseudomonas* spp. Phytopathology 85:1028-1032.

Savary S, Elazegui FA, Moody K, Litsinger JA. 1994. Characterization of rice cropping practices and multiple pest systems in the Philippines. Agric. Sys. 46:385-408.

Schoenly KG, Cohen JE, Heong KL, Litsinger JA, Aquino GB, Bimrrion AT, Arida G. 1996. Food web dynamics of irrigated rice fields at five elevations in Luzon, Philippines. Bull. Entomol. Res. 86:451-466.

Settle WH, Araiwan H, Astuti ET, Cahyana W, Hakim AL, Hindayana D, Lestari AS, Pajamingsih. 1996. Managing tropical rice pests through conservation of generalist natural enemies and alternative prey. Ecology 77:1975-1988.

Slovic P, Fishhoff B, Lichtenstein S. 1977. Behavioral decision theory. Annu. Rev. Psychol. 28:1-39.

Song WY, Wang GL, Chen L, Kim HS, Pi LY, Gardner J, Wang B, Holsten T, Zhai WX, Zhu LH, Fauquet C, Ronald PC. 1995. A receptor kinase-like protein encoded by the rice disease resistance gene Xa21. Science 270:1804-1806.

Tabashnik BE. 1994. Evolution of resistance to *Bacillus thuringiensis.* Annu. Rev. Entomol. 39:47-79.

Tang W, Yang T. 1997. Research and application of biocontrol of plant diseases and PGPR in China. In: Ogoshi A et al, editors. Plant growth-promising *rhizobacteria* —present status and future prospects. Hokkaido University, Sapporo, Japan. p 1-9.

Tatum LA. 1971. The southern corn leaf blight epidemic. Science 171:1113-1116.

Teng PS. 1994. Integrated pest management in rice. Exp. Agric. 30:115-137.

Teng PS, Fischer KS, Hossain, M. 1995. Meeting the food challenges of the 21st century: the role of national and international rice research. Trop. Biol. 1:1-21.

Teng PS, Hossain M, Fischer KS. 1995. Developing an R&D model for the humid tropical ecoregion in Asia. In: Ecoregional approaches for sustainable land use and food production. Bouma J, Kuyvenhoven A, Bouman BAM, Luyten JC, Zandstra HG, editors. Netherlands: Kluwer Academic Publishers. p 305-332.

Vijante V, Heinrichs EA. 1986. Rice growth and yield as affected by the whorl maggot, *Hydrellia philippina* Ferino (Diptera: Ephydridae). Crop Protect. 5:176-181.

Waibel H. 1986. The economics of integrated pest control in irrigated rice. Berlin: Springer-Verlag.

Wang GL, Mackill DJ, Bonman JM, McCouch SR, Champoux M, Nelson RJ. 1994. RFLP mapping of genes conferring complete and partial resistance to blast in a durably resistant rice cultivar. Genetics 136:1421-1434.

Way MJ, Heong KL. 1994. The role of biodiversity in the dynamics and management of insect pests of tropical irrigated rice — a review. Bull. Entomol. Res. 84:567-587.

Wu C, Zhao R, Zhang C, Wang J, Bentur J, Datta S, Cohen M, Fan Y. 1996. Transgenic rice plants resistant to yellow stem borer. Abstracts of the East Asia Regional Meeting of the International Program on Rice Biotechnology. p 6.

Yoshimura S, Yamanouchi U, Katayose Y, Toki S, Wang Z, Kono I, Kurata N, Yano M, Sasaki T. 1997. Map-based cloning of *Xa21,* a bacterial blight resistance gene in rice. Abstract No. 613. In: Book of Abstracts. Fifth International Congress of Plant Molecular Biology, 21-27 September 1997, Singapore.

Annex 1. Regional differentiation in rice production systems in China.

Region	Rice production system	Province/municipality
North	Single-crop rice, japonica, irrigated, with medium-high yields	Liaoning, Jilin, Beijing, Tianjin, Hebei, Shandong, Henan, Shanxi, Shaanxi, and Gansu
Center	Mixture of single and double-crop rice; predominantly double-cropped indica with medium-high yields. Some parts with rice-wheat system.	Hunan, Hubei, Anhui, Jiangxi
Coast	Mainly single-crop rice; indica and japonica; medium-high yields; region facing results of economic growth such as rural labor shortage and loss of rice land.	Jiangsu, Zhejiang, Guangdong, Fujian, Shanghai, Hainan
West	Single-crop rice; indicas with medium-high yields. High yield variability due to differences in environment, especially thermal units for rice growth.	Sichuan, Guangxi, Yunnan, Guizhou, Chongqing

Precision farming for intensive rice systems in Asia

Achim Dobermann and Mark Bell

International Rice Research Institute, MCPO Box 3727, 1271 Makati City, Philippines

Rice demand is expected to increase by approximately 4 million t year^{-1} over the next 30 years, equivalent to adding around 1 million ha of new land per year at the present world average yield levels. Such land is not available, and so we must increase the efficiency of present production systems.

Increasing yields and input use efficiency will require new farming concepts that focus on fine-tuning of seed, nutrient, water, pesticide, energy, and labor inputs for smaller management units. *Precision farming, prescription farming,* or *site-specific crop management* (SSCM) are frequently used new terms to describe such emerging technologies (Robert et al 1995b). They originated as a response to the increasing awareness of the large variability between and within production fields. However, the premise underlying site-specific management, namely that heterogeneity (particularly that of soil) influences the productive potential of agricultural land, is not a new concept (McBratney and Whelan 1995). First attempts to continuously manipulate farming operations date back to 1925 or even earlier, when Haynes and Keen used a dynamometer to draw maps of plow resistance (Haynes and Keen 1925).

During the past 20 years, research has provided many examples of detailed investigations of magnitudes and sources of spatial and temporal variation of climate (Hubbard 1994, McBratney 1985), topography (Huang and Bradford 1992), soil properties (Beckett and Webster 1971, Burgess and Webster 1980, Burrough 1993, Webster 1985), weeds (Chancellor and Goronea 1994, Dessaint and Caussanel 1994, Donald 1994), diseases (Lannou and Savary 1991, Larkin et al 1995), nematodes (Webster and Boag 1992), and other production factors at scales that are relevant for producers. Due to the evolution of computers and electronic, pneumatic, and hydraulic devices, the technologies for managing this variability have now become available (Robert et al 1995a).

In this paper, we tried to assess opportunities, realities, and requirements for "precision" farming in rice-based cropping systems of Asia. We restricted the discussion to intensive, mostly irrigated rice systems as the concepts and technologies proposed are currently mainly of interest to those farmers; however, certain concepts will be applicable to other ecosystems. Many irrigated farmers have achieved tremendous yield gains during the past 30 years, often approaching economically attainable yields. However, average yields of irrigated rice have to increase from 4.9 t ha^{-1} in 1991 to about 8 t ha^{-1} in 2025 (Cassman and Pingali 1995). Thus, irrigated rice farmers will have the greatest need to fine-tune their farm management to produce the bulk of the future increase in rice supply. At the same time, positive awareness of environmental aspects of farming means that farmers have to ensure sustainability and environmental compatibility of their systems. They will have to move from simple general decisions and recommendations to much more knowledge-intensive, site-specific crop management (Fig. 1).

The questions we tried to answer were:

1. What are the principles of site-specific crop management?
2. What are the current realities and major limitations of site-specific crop management in developed countries?
3. What are the opportunities for site-specific crop management in irrigated rice?

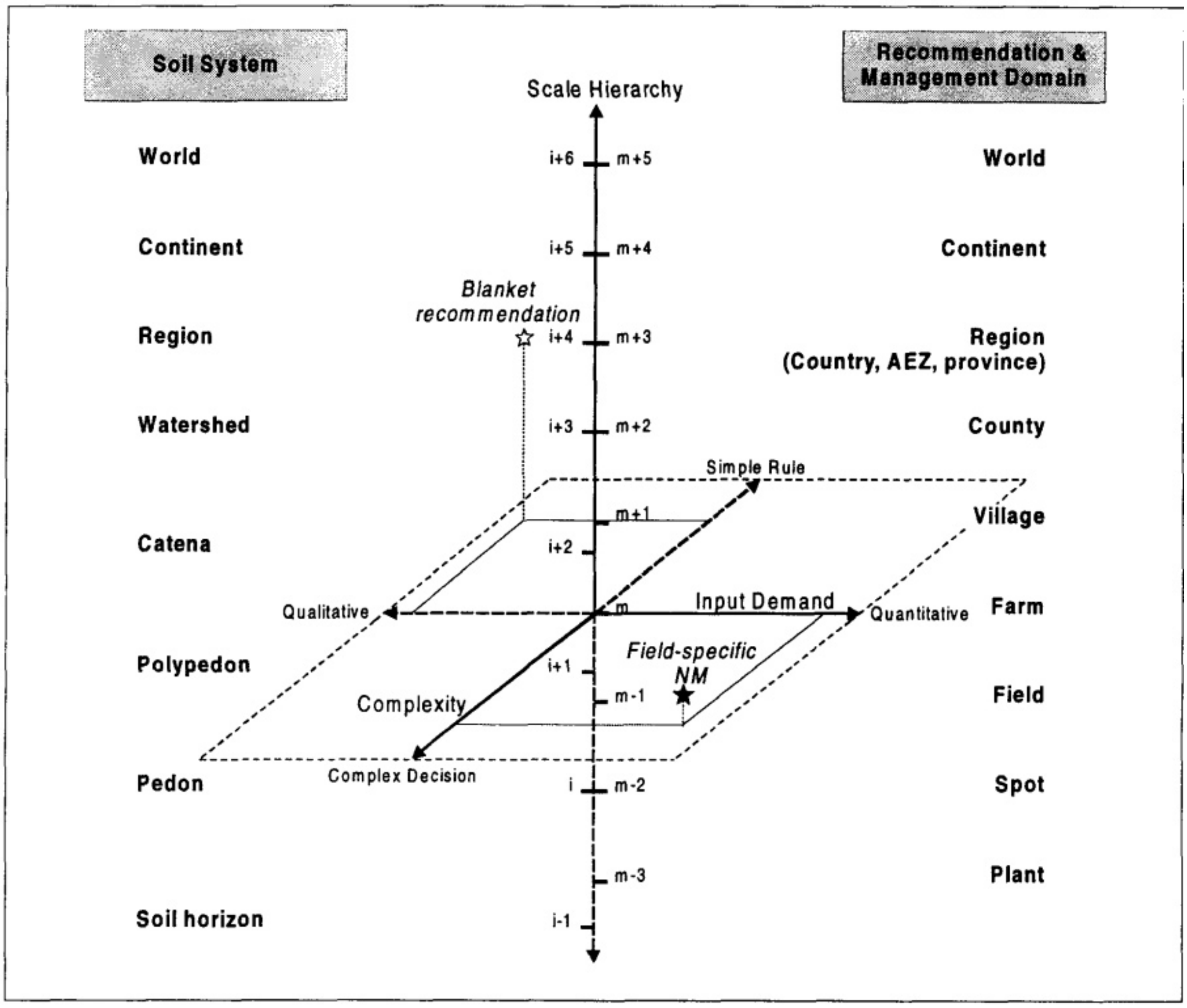


Fig. 1. Classification of crop management operations according to spatial scale (y), input demand (x), and complexity of information processing (z). The approximate positions of blanket and field-specific fertilizer application are drawn as examples. Modified from Hoosbeek and Bryant (1992).

Definition of farm and site-specific crop management

Most of the terms previously proposed are limited in scope to managing spatial variability and/or variability within a single field using specialized machinery (Appendix 1). However, certain operations in a precision or site-specific farming approach can be uniform for several fields or even farms and one should also consider the relationships between different farms and between different commodities within a farm.

We consider precision farming as a scientific concept that is applicable to farms and fields of all sizes, including those found in Asia. Therefore, we propose three terms for characterizing modem farming operations: (1) total farm management, (2) site-specific crop management, and (3) technology application domain (Fig. 2).

Total farm management (TFM) is an information-based agricultural management system that provides an optimum balance between profitability, food production, and sustainability within a single farm by

- maximizing output and utilization efficiency of all production inputs,
- optimizing flows of nutrients, water, energy, machinery, and labor,
- adding value to production,

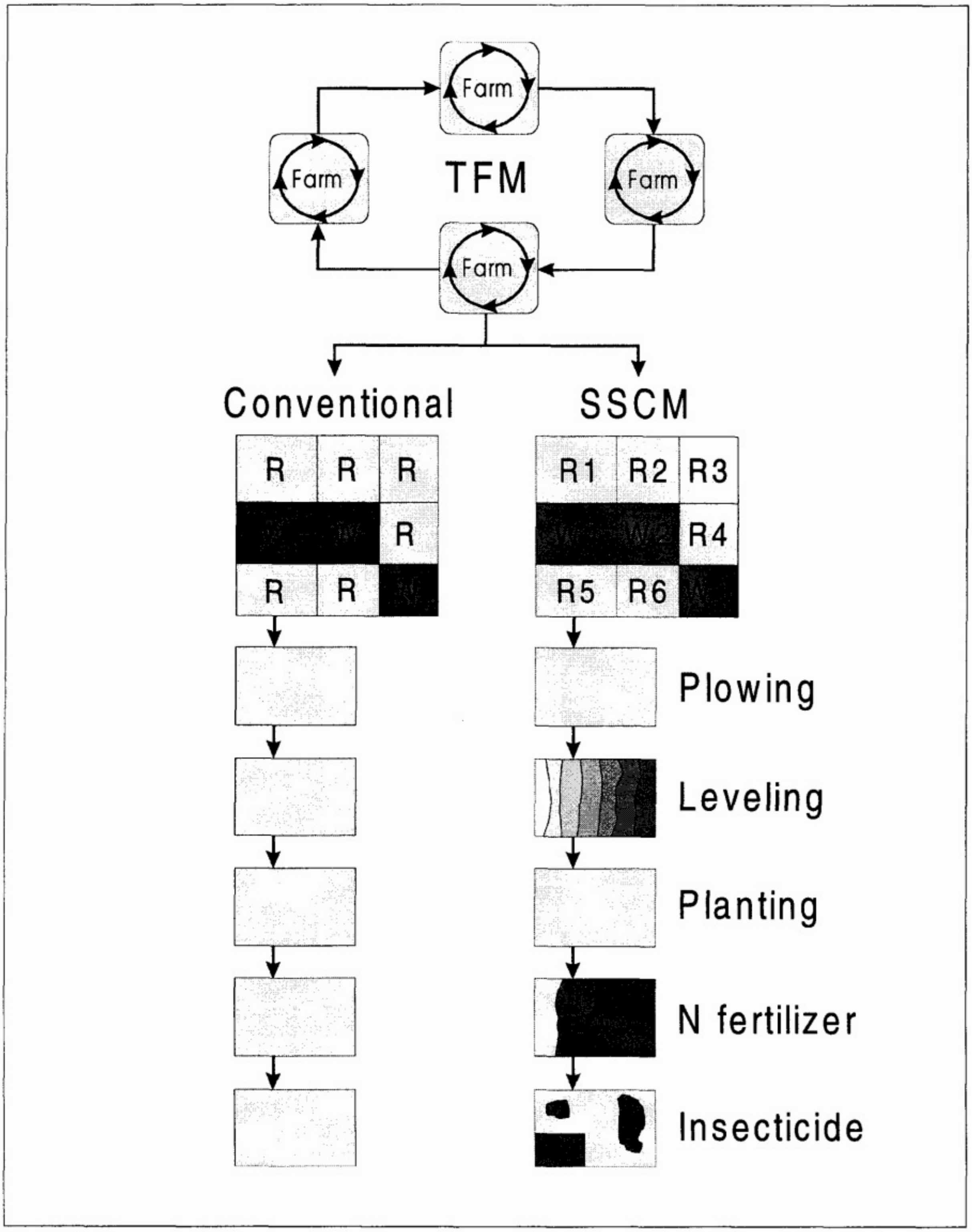


Fig. 2. Site-specific crop management (SSCM) operations vs. conventional farm management. At the whole farm level, relationships within and between farms are directed by total farm management (TFM). At the field level, in the conventional approach all fields planted to the same crop (e.g., rice/R or wheat/W) are managed similarly and applications do not vary much between and within fields (left side). In the SSCM approach, each field planted to the same crop may be treated specifically (e.g., R1 is different from R5). Depending on the technology available, some operations vary between and within fields (right side), i.e., technology application domains range from small patches to the whole farm.

For each farm size a precision management approach can be designed with technologies differing according to biophysical and socioeconomic conditions.

- minimizing off-farm effects on soil, water, and air quality across different production systems within the farm and between farms.

This definition emphasizes optimization of management of a whole farm, including various cropping systems and, if applicable, other types of agricultural production. At this level, a farmer has to make decisions about the allocation of major inputs and any optimization attempts should also consider relationships with other farms in a neighborhood of varying sizes. The latter include buy-and-sell operations, rental of machinery and labor, credits, distribution of manure, and postharvest activities. Considering the differences in population distribution, a village is probably the most appropriate scale for such between-farm operations in Asia, whereas in North America such operations may have much less weight (and perhaps would be defined for an environmental unit such as a watershed). TFM mainly requires the right intellectual concepts and tools (software) for collecting, analyzing, and interpreting relevant information.

Site-specific crop management is the crop-specific use of local soil, crop, and climatic parameters to make precise applications of production inputs to technology application domains with different characteristics. Typical components that form the SSCM of a particular crop are varying the depth of soil tillage based on topography, changing varieties or sowing rates according to soil types, adjusting the fertilizer application rate according to variation in soil test values, selective liming of certain fields or field parts only, or varying the pesticide spray rate based on actual crop stress.

This definition emphasizes management of a single crop according to site characteristics.

Technology application domains (TAD) are, for a specific technology, the smallest uniform spatial units that can be treated differently. Within an SSCM approach, the size of TADs can be different for different crop management operations and depends on

- site characteristics with the greatest influence on growth of the specific crop,
- relationship between additional net return from differentiated treatment (value/cost ratio) and size of TAD, and
- technical feasibility for collecting information and applying inputs at different spatial scales.

Therefore, SSCM decisions and operations may include continuous on-the-go adjustment, applications specific to patches within a single field, uniform applications to single fields, or uniform applications to groups of several fields with similar properties. This definition of TAD emphasizes a specific technological solution for implementing a certain crop management operation according to site characteristics.

General practice of site-specific crop management

A typical SSCM application includes the following steps (Fig. 3):

1. Knowledge capture: Identify and quantify (map) the variability of key input parameters at the scale needed to make a decision about the specific SSCM operation.
   - What is the information to monitor?
   - What are the suitable tools to quantify the variation in the key information?

2. Knowledge interpretation: Translate the information into decisions about management (application) by understanding the sources of variability and its impact on yield.
   - What tools are available/needed for this information to be interpreted?
   - What does the collected information mean for crop management?
   - What are the appropriate crop management options?

3. Application: Identify the available application technology and the optimal size of

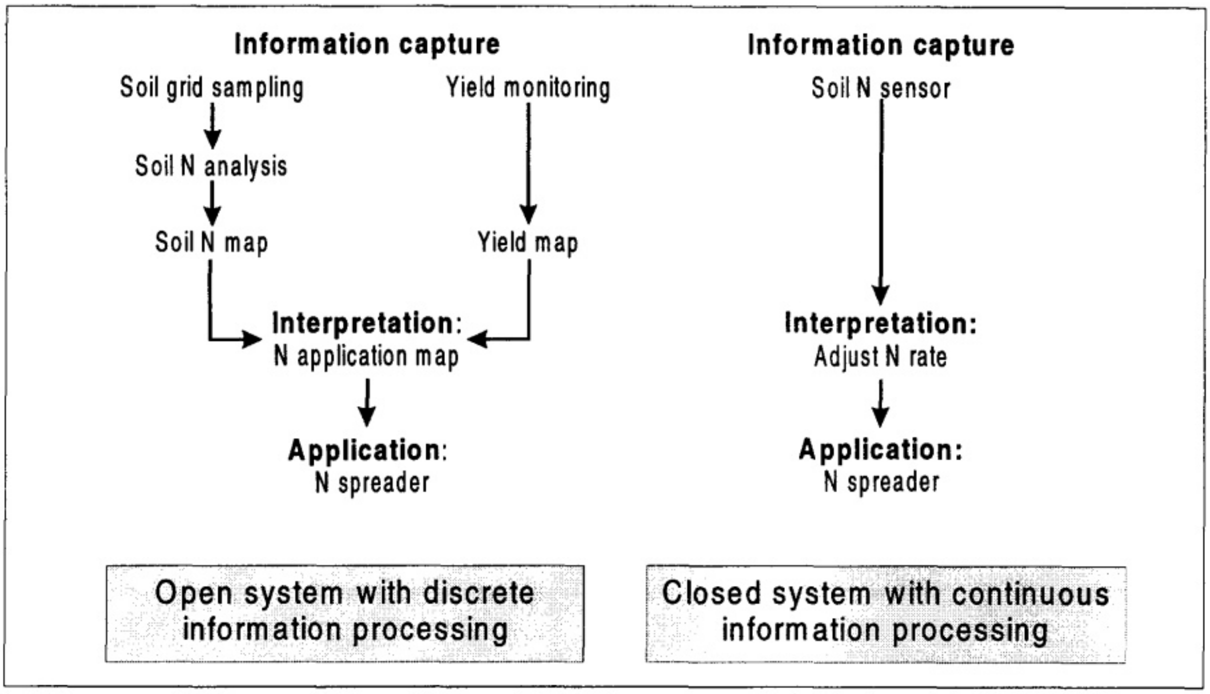


Fig. 3. SSCM technologies for managing variability within fields differ in their information flow. Fertilizer N application is shown as an example.

the technology application domain. Apply differential amounts of inputs to the TADs.

- What technologies are available/needed to apply the treatment?
- How can the whole approach be communicated and implemented?

Based on the kind of information processed we can classify SSCM approaches into (1) univariate (single measurement and action), (2) multivariate (multiple measurements and actions), and (3) historical (use of multiple crop years). For information flow, we can further distinguish two types of SSCM applications for managing variability within a field (Fig. 3), namely (1) systems with discrete steps on information processing, and (2) systems with continuous information processing. More discussion of information processing in SSCM is found elsewhere (Schueller 1992, 1997).

Systems with discrete steps of information processing

In a discrete system, information is captured in one or more temporally separate steps (e.g., soil sampling and analysis or yield monitoring). Interpretation of information is done in a second step by combining new with already existing data to produce an application decision. In a third step, the application is carried out. Important features of this technology include:

- A real-time positioning system is required for geo-referenced collection of information and for variable rate application.
- A minimum lag time of several days or weeks occurs from sampling to application.
- Much of the information processing is done off-farm.
- Each discrete step is subject to error.

Systems with continuous information processing

In a continuous system, information is captured automatically in real time using on-the-go sensors, immediately processed in a computer on board (including combining it with previous information), and the applicator is immediately adjusted (McBratney and Whelan 1995). Thus, as the machine drives over the field, information is gathered and tillage depth, fertilizer rate, sowing rate, etc., are adjusted accordingly. Important features of this technology include:

- A real-time positioning system may not be required for operations that only require measuring one or a few variables on the go.
- Accurate and robust on-the-go sensors are needed.
- Lag time from sampling to application is only a few seconds or less.
- Information processing is done on board.
- Steps such as sampling error, interpolation error, or positioning error are either significantly reduced or eliminated.
- Precise variable-rate technology (VRT) and a high degree of synchronicity between speed, information processing, and adjustment of the applicator are needed.

Obviously, equipment like this would eliminate many of the difficulties and uncertainties associated with the current discrete approach. The major bottleneck in developing complete continuous application solutions is the availability of suitable on-the-go sensors and adequate production functions for identifying correct treatment for given characteristics at a given location.

Potential benefits of SSCM

The basis of SSCM is that fields are highly variable (both between and within) and new technologies are available that can characterize that variability and delineate meaningful management zones to optimize supply and demand of nutrients, water, energy, and other resources according to their variation in time and space (Fig. 3). Where there is less supply (e.g., certain fields or certain locations within a field), application has to be greater than in physical land units with higher supply and vice versa. At the farm level, expected benefits are:

- increase in total production by higher yields
- improved use efficiency of nutrients, water, pesticides, and other key farm inputs (greater yield per unit input)
- greater profitability
- enhancement and maintenance of soil fertility
- reduced negative impact on the environment by greater crop use of inputs and so less loss to the environment
- rural communities benefit: increased cash flows and creation of additional jobs
- increased farmers' knowledge and awareness about soil and crop management

The latter is difficult to measure, but very important. For the first time, many farmers have hard data about variability in growth in their fields. Even though interpretation of a yield map or maps of soil test values is a difficult task, the map alone is a real eye-opener and farmers have become very interested in fine-tuning soil and crop management in their fields.

Cost-return analysis on specific practices is important so that their individual contribution to profitability can be determined (Reetz Jr. and Fixen 1995). But there is still a substantial lack of good quality research on costs and benefits of SSCM. Potential net benefits for the farmer and for the environment (Fig. 3) depend on

- additional equipment and operational costs required,
- quality of capturing and processing the right information into the right decision, and
- precision of application (VRT).

Current SSCM realities

Important tools include positioning systems, sampling and mapping procedures, sensors for continuous measurement of crop yield (yield mapping), on-the-go sensors for continuous measurement of some soil properties, real-time weed and pest damage recognition systems, software and hardware for data storage and decision making, and VRT for precise continuous adjustment of application rates (McBratney and Whelan 1995, Robert et a1 1995b). Appendix 2 summarizes the state-of-the-art for specific components of SSCM.

The degree of variability, the quality of the input information, the approaches used to translate it into application decisions, and the costs associated with differentially managing a field determine the benefits obtained from SSCM. The more variable the environment, the greater the economic and environmental benefit from SSCM will be.

Fertilization is the dominant SSCM application. Fertilizer spreaders or liquid applicators for variable application are readily available in different sizes. Compared to conventional (uniform) fertilizer application, differential application increases the cost by approximately 10-15% (Reetz Jr. and Fixen 1995, Wollenhaupt and Buchholz 1993). Whether gains in net return can be achieved depends on the degree of variability in soil nutrients, the quality of measuring and translating it into an application map (i.e., understanding of the production function), and the precision of application. Increase in net returns is usually lowest in field parts with already high nutrient status. Average increase in profit is highest in fields with a generally low nutrient level.

Weeds tend to be spatially aggregated, making them easier to sense. Decisions about spraying or not spraying or continuous variation of the rate are options for site-specific weed management. Intermittent herbicide applications based on actual infestation can reduce herbicide use substantially (Mortensen et al 1995). The VRT for this is available, but the field sampling required to describe weed seedling populations is a significant limiting factor in implementing this technology. Presumably, variable rate application of pesticides will always require continuous, real-time data acquisition systems (Fig. 3, right) to be fully efficient. Recent developments in sensor or real-time weed recognition technology (Felton et a1 1991, Woebbecke et a1 1995) are promising and we may expect similar solutions for managing insect and disease pests on-the-go. So far, integrated pest management (IPM) in SSCM has not received enough attention.

Other developments include VRT for site-specific soil tillage, anhydrous ammonia application, liming, drill seeding, or sprinkler (pivot) irrigation (Robert et al 1993, 1995b).

Despite all the excitement about new farming technologies such as SSCM, we must be aware of the problems that are associated with them. Schueller and Wang (1 994) present a good summary of some of the considerations for fertilizer and pesticide application. Many of the new tools are impressive, but the currently dominant “discrete” SSCM approach (Fig. 3, left side) has many shortcomings. What if the variability is miscalculated and the application maps fed into the controller are not accurate? What if the applicator cannot react sensitively enough to the variation in soil nutrients? For example, in the variable application of nutrients, the following problems may occur:

1. Error associated with information capture: The current SSCM solutions for fertilizer application are all based on soil grid sampling. Success depends directly on whether the sampling procedures used can actually resolve the spatial variation at a level that allows useful interpolation.

- The largest proportion of the overall variation in available soil nutrients usually occurs over short distances (Beckett and Webster 1971, Burrough 1993). Up to half of the variance within a field may already be

Sophisticated VRT is available, but if used in combination with application maps that are obtained from rather simple procedures with limited accuracy, use of VRT creates pseudo-accuracy. Agronomists must distinguish deterministic sources of yield variability from those that are stochastic.

There are situations where the investment in sampling, sample processing, computing, and variable application will not pay off simply because theoretical assumptions do not hold. This applies to any SSCM technology, whether it is a high-tech one applied to large fields or a low-tech one used in small fields.

Many of the shortcomings associated with the discrete information collection and processing concept (Fig. 3, left) can only be overcome by developing continuous, real-time information collection, processing, and application equipment (Fig. 3, right).

present in any square meter in it (Beckett and Webster 1971).
- Within a single field, magnitudes, scales, and sources of variation are different for different soil properties (Dobermann et a1 1997a, Webster and McBratney 1987). Any “optimal” sampling scheme is only a compromise to obtain information about different soil properties simultaneously. Reliance on soil grid sampling is perhaps the greatest source of error in current variable fertilizer application technologies.
- The soil test chosen may not accurately reflect potential soil nutrient supply.
- The laboratory error may be too large.
- All interpolation techniques will give a map, but the quality of a map is often not known (Burrough 1993). Any map is only a rough model of the reality. Most interpolation techniques smooth the data so that extreme large and small values are made invisible. These extremes may be important. When the sampling distance used does not allow clarification of the most important scales of variation in soil nutrients, interpolation is meaningless and the best estimator of the field nutrient status (and hence crop response to applied nutrient) would be the mean of all samples collected, not an interpolated map representing a pseudo reality.

2. Error associated with interpretation of information: The method used to calculate the application map(s) may be inaccurate.
- Currently, most calculations are based on simple empirical models (fertilizer response curve or nutrient balance/nutrient replenishment concept). Those empirical relationships were often developed over a much wider range of soil types. Are they compatible with site-specific management? Crop response to interactions of nutrients is often neglected and more sophisticated crop models are hardly used because of lack of input data.
- Processing time may be too long. Temporal variability of soil nutrient status may equal or even exceed spatial variability (Beckett 1987, Dobermann et al 1994). If information processing is too slow, the application map is not fully relevant anymore. In the most developed SSCM regions of North America, the minimum time from soil sampling to generation of application map is about 3 days, but is often much more.

3. Application error: The minimum application area (TAD) may exceed the scale at which most of the variability occurs.
- Cruising over the field at speeds of at least 30-40 km h^{-1} with a spread of 21 m within 1 sec, the Terra Gator (see Appendix 2) applies fertilizer in an area of 175-235 m^2. The actual feasible response time for smooth adjustment of the applicator is probably even larger than 1 sec so that any soil variability occurring within 200-300 m^2 is already neglected.

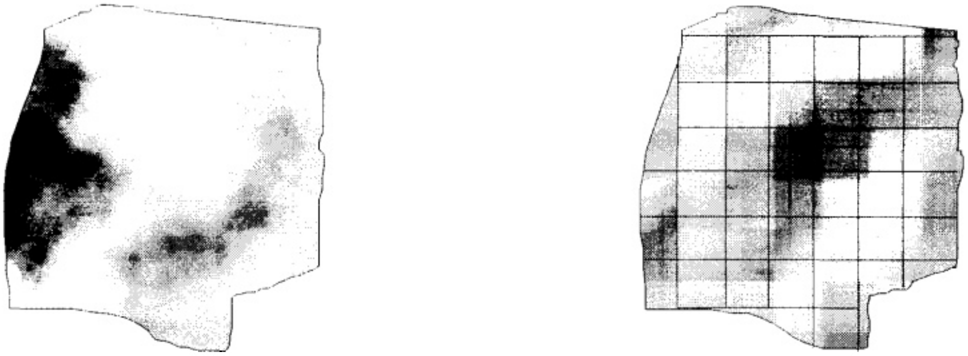
Thus, although new tools are promising, we have to know where we can use them to justify acquisition and operational costs. There is an eminent lack of research on quantitative error assessment in SSCM to (1) distinguish the different sources of errors in all major steps (information capture, processing, application), (2) identify how errors propagate throughout the whole operation, and (3) quantify the precision that is always claimed. The statistical techniques for doing this are available (Heuvelink 1993, Leenhardt 1995), but no such attempt to assess quantitative errors is known to us. These techniques would certainly help to refine SSCM.

Opportunities for SSCM in intensive rice systems of Asia

Is SSCM necessary?

Crop management recommendations over the past four decades in Asia were driven by the increasing use of externally provided inputs and the so-called “package approach’ based on blanket recommendations over wide areas (Byerlee 1996). Should and can we apply the principles of SSCM to manage irrigated rice fields in Asia? We believe that yes we can because recent research in lowland rice areas has demonstrated that

Generally, SSCM in Asia can be built around much less sophisticated technology than implementing SSCM in large fields, where global positioning systems (GPS), mapping systems, computer technology, and VRT are minimum requirements (Fig. 4).



Heterogeneous treatment of a large field according to variation of soil P supply and crop P demand within a single field

1. Create digital maps of soil P supply and maps of past yields [1]
   - Conduct soil grid sampling.
   - Conduct soil P analysis on all grid samples.
   - Translate soil P test values into estimates of soil P supply (kg ha^{-1}).
   - Interpolate soil P supply map from grid values.
   - Measure past yields with high resolution using a yield monitor mounted on a combine and equipped with a global positioning system (directly creates yield map with high resolution, no interpolation).
2. Create digital application map showing the different amount of P to be applied to different parts of the field
   - Estimate amount of P to be applied for each pixel on the map (based on estimates of soil P supply and crop P removal; overlay soil maps and yield maps by using empirical models of fertilizer response for a specific yield target).
3. Apply P using variable rate technology and geo-referencing system (GPS)
   - Feed application map into the computer.
   - Apply varying rates of P according to the position in the field.

Homogeneous treatment of a single small field based on average, field-specific soil P supply and crop P demand (Dobermann 1996)

1. Estimate average soil P supply
   - Conduct soil sampling to obtain one composite sample per field. [2]
   - Conduct soil P analysis on one sample.
   - Estimate potential soil P supply (kg ha^{-1}).
2. Predict amount of P to be applied to the field
   - Estimate amount of P to be applied to the whole field (based on a nutrient supply - nutrient uptake - grain yield model that accounts for interactions between N, P, and K).
3. Apply P using conventional technology

[1] If desired, determinations of other soil properties could also be done to improve the prediction of soil P supply.

[2] If tools for *in situ* measurement of soil P supply are available (resin capsule or P omission plot), no soil sampling is required.

Fig. 4. Managing variability within (large) fields requires different SSCM technology than managing (small) fields on a field-specific basis in which less attention is paid to variability within the field. The detailed steps in application of P fertilizer are shown as an example.

- there is large variability in stable soil properties, soil nutrient supply, nutrient use efficiency, other production factors, grain yield, and economic performance between rice farms or between single rice fields (Angus et al 1990, Cassman et al 1996, Dobermann et al 1997a, Dobemann and Oberthuer 1997b, Oberthuer et al 1996, Olk et al 1996, Pinnschmidt et al 1994, Ueno et al 1988), and
- even within very small rice fields, tremendous variation in yields and yield components exists that is caused by microvariation in soil nutrients, land

leveling, crop emergence, weeds, and other pests (Baki 1993, Dobermann 1994, Dobermann et a1 l994, 1995, 1997a, 1997c, Gravois and Helms 1994, Miller 1990, Or and Hanks 1992).

This led us to conclude that significant gains in productivity and input use efficiency can be achieved by soil and crop management technologies that are much more tailored to the specific characteristics of individual farms, rice fields, and variation within fields (Cassman et a1 1997, Dobermann et a1 1996). We are also convinced that the methods for characterizing, interpreting, and managing variability in large fields can also be used for smaller fields found in irrigated rice-cropping systems. Farmers already integrate a lot of knowledge and often already have a sense of the variability they have in fields and crops (eg, which fields are typically weedy, which fields or parts of fields always give a higher yield, etc.). What we need are more reliable tools to support them in their decisions.

Is SSCM feasible?

While much of the purpose of precision farming in developed countries is to break down variability across large fields to smaller uniform units, in Asia much of this division has already taken place due to the typically small farm size. Conceptually, adjusting tillage, sowing, fertilizer, or pesticide rates separately for many small fields or farms (<1 ha to 5 10 ha) in an Asian domain is similar to adjustment according to soil variation within a large field (>10 ha to 2 100 ha) in North America. There is a continuum, however, as there is still variability within these small fields. An "Asian variant" of SSCM in the intensive rice system would probably include operations at different spatial scales and with very different information demand. The first major step is to refine regional recommendations to individual field-level recommendations — further advances can be made in the future to within-field recommendations.

Practical options for SSCM in irrigated rice are very much determined by the general shifts in these production systems, including:

- Labor shortages – fewer agricultural field workers.
- Water shortages for rice – less water for agriculture as urban demands and alternate uses increase.
- Less land for rice production – as cities grow over production areas and alternate land use increases.
- Shifts in rice quality preferences – as economies develop throughout the region, quality preferences will become more important in some countries.

With these trends in the socioeconomic farming environment, we expect to see significant changes in the structure and production technologies of Asian rice farms (Fig. 5). The major scenario is one of technological changes triggered and driven by increasing labor cost for agriculture and socioeconomic changes favoring the formation of relatively larger farms and adoption of mechanized technologies. Land preparation, crop establishment, harvest, and postharvest activities are labor-intensive farm operations and farmers will increasingly seek ways to reduce costs associated with them. They will also seek ways to add value to production by improving the quality of harvest or improving use of various by-products.

There are many linkages between the processes shown in Fig. 5, because they are driven by socioeconomic changes such as the increasing cost of labor and other agricultural inputs or prices for agricultural commodities. In some advanced post-Green Revolution areas such as the Indian Punjab, Thailand, or parts of China, many of these transformations have already started, whereas other regions may not be much affected at all during the next decade.

Ongoing and expected socioeconomic changes in rice farming create opportunities for establishing new, site-specific crop management concepts.

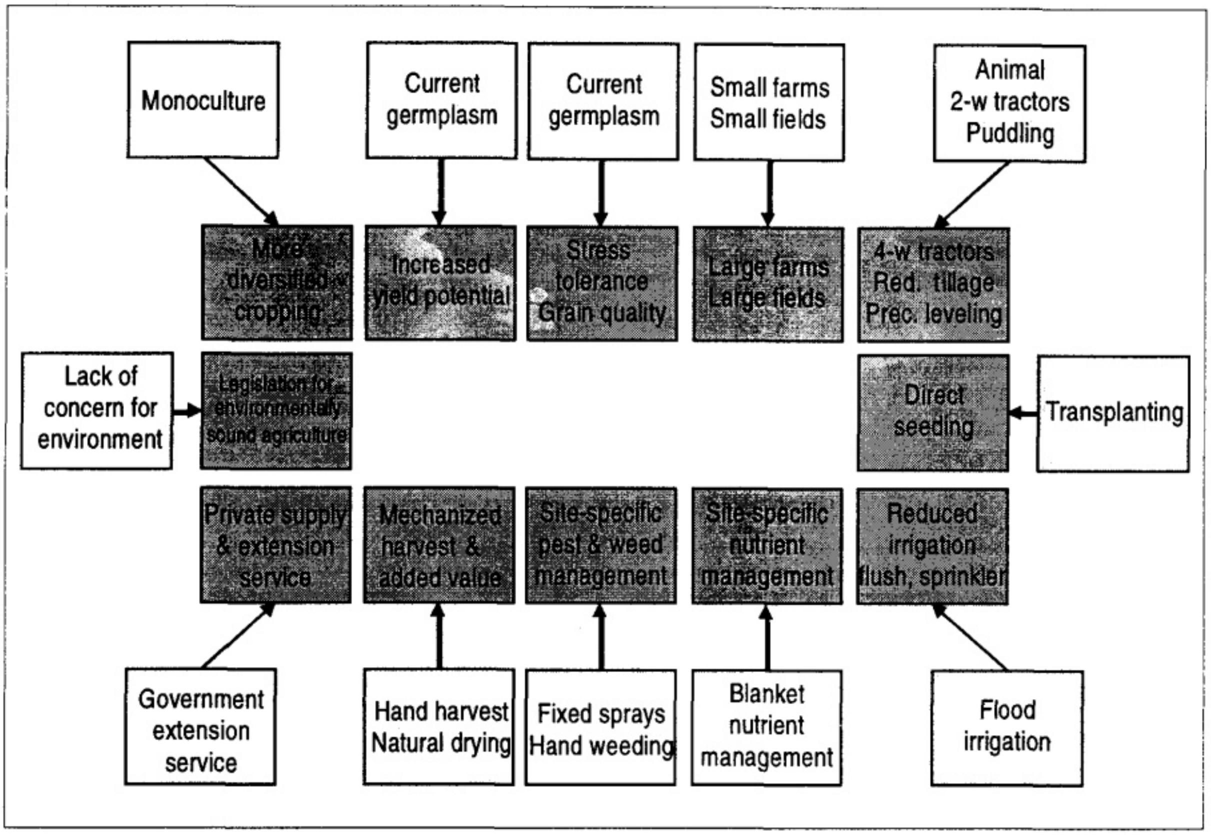


Fig. 5. Pathways of future intensification of soil and crop management in intensive, irrigated rice systems.

The target group: irrigated rice farmers in Asia

To identify potential and suitable technologies for SSCM in irrigated rice, we need to understand the variation in socioeconomic farm characteristics among countries and regions within a country. There are about 30 to 60 million irrigated rice farms in Asia[1] and they differ in their needs for modern farming practices. Appendix 3 shows fundamental farm characteristics for a sample of intensive rice farmers from key irrigated rice domains in South and Southeast Asia (Moya et al 1997). Farm sizes, education, sources of income, labor input, crop management methods, and proportional costs of key production inputs vary widely among regions and within each domain (data not shown).

In this sample, Tamil Nadu farmers represent those with the highest labor input and a very low degree of mechanization. In Tamil Nadu, all rice is still transplanted, pesticide use is low, almost no herbicide is applied, most farmers apply fertilizer in four or even five splits, and most harvest/postharvest activities are done by hand. Intensive crop care resulted in high average yields of 6.4 t ha^{-1} (Appendix 3). As we move from the Mekong Delta to Central Luzon and Central Thailand, we can distinguish a trend of decreasing labor use, increasing mechanization, adoption of direct-seeding, reduction in the number of N split applications, increasing pesticide use, and increasing field and farm sizes. In Central Thailand, farms have become larger than in many other regions, adoption of wet seeding is 100%, soil tillage is

---

[1] The total harvested area of irrigated rice is 74 million ha per year. Of this, 22 million ha are cropped with rice-wheat (= 22 million ha physical area), 30 million ha are cropped with rice-rice-rice (about 14 million ha physical area, of which 12 million ha are under rice-rice and 2 million ha are under triple cropping), and 22 million ha are cropped with other rice-based systems (= 22 million ha physical area). Assuming average farm sizes (under rice) of 1 to 12 ha per farm (Table 1), we get (22 + 14 + 22) / (1 or 2) = 29 to 58 million farmers.

done by 4-wheel or at least 2-wheel tractors, pesticides are heavily used (weed control), and combine harvesting is predominant. Thus, total labor input is only 15 person-days ha^{-1} compared with 210 person-days ha^{-1} in Tamil Nadu (Appendix 3).

In the adoption of different SSCM technologies, we can distinguish three major types of rice farms:

Type I: small, labor-intensive farms

Farms (4-2 ha) and individual fields are small (usually <0.2 ha) and mechanization is limited to the use of 2-wheel tractors or other smaller equipment for land preparation. Transplanting is the dominant crop establishment method and harvest is done by hand. Much family labor is involved. The ratio of income from rice and income from other activities may vary widely. Use of production inputs and farmers' decisions depend very much on the financial situation.

In such farms, site-specific management will probably be limited by the low degree of mechanization, limited financial resources for contracting services or buying better inputs, and limited access to the required expertise. There will, however, be options to focus on managing fields on a per-field basis using simple technologies and tools for decision making. We find such farms in regions such as the Red River Delta (Vietnam), Java (Indonesia), and South India, but also in many parts of rural China.

Type 2: small-medium, less labor-intensive farms

Farms (3-5 ha) and individual fields (>0.2-1 ha) are of medium size and mechanization is already more advanced. Land preparation is done by 2- or 4-wheel tractors, many farmers use direct-seeding for crop establishment, herbicides are used for weed control, harvest is done by hand or small combines, and postharvest operations are mechanized. Rice production is a major source of total farm income and much contract labor/rented service is involved. For SSCM, both field-specific operations (basal fertilizer application, sowing, harvest) and managing variability within a single field are feasible (precision leveling using small laser technology; weed, insect, and disease control based on observation; N topdressed application). We find such farms in the Mekong Delta (Vietnam), Central Luzon (Philippines), Central Thailand, Northern India, and Malaysia.

Type 3: medium-large, mechanized rice farms

Farms (>5-10 ha) and individual fields (>1 ha) are larger and most operations are mechanized. Direct-seeding is predominant, 4-wheel tractors are used for tillage, and combine harvesting is common. These are more commercial rice farms where rice is the dominant source of income. A wide range of SSCM technology can be used, including treating fields homogeneously or based on variability within the field for most crop management activities (Fig. 2). These are farms where current SSCM concepts and VRT developed in North America and other countries can be used. In Asia, there are not many rice farms of this type. We might find them, for example, in Central Thailand, Malaysia, and Northern India, or, more recently, as pilot farms in southern China.

Technologies for SSCM in Asia

The issue of application scale (Fig. 1) leads to two questions, namely: (1) Where can large-scale technologies be applied within rice farms of Asia? and (2) What technologies are scale-neutral or particularly suited for small rice farms? For large-scale automated systems, we can draw directly from experience in other countries. However, options for small to medium-scale applications are required.

Within-field management options will depend upon (1) tools and farmer skills available (knowledge capture), and (2) sources of information available to farmers (for

There is no such thing as a "typical" irrigated rice farmer; thus, our recipes for modern farming must be tailored to different groups of farms. Their socioeconomic and biophysical differences determine the choice of site-specific technologies.

Table 1. Examples of technologies for site-specific crop management operations in large and small rice farms.

	Component of site-specific crop management	Technologies for large irrigated rice farms (highly mechanized)	Technologies for small irrigated rice farms (partly mechanized)
Homogeneous treatment of a single field (field-specific application)	Soil tillage	4-wheel tractor	2- to 4-wheel tractor, buffalo
	Crop establishment	Direct-seeding, 4-wheel tractor/aircraft	Transplanting or direct-seeding, by hand, mechanical transplanter, row seeder
	Mechanical weed control	4-wheel tractor	Hand-weeding
	Pesticide application	4-wheel tractor + sprayer, aircraft, field-specific or general recommendation	Hand-held sprayer, field-specific or general recommendation
	Fertilizer application	Conventional machinery or aircraft, field-specific soil test recommendation, plant diagnosis	By hand, general or field-specific recommendation, plant diagnosis (SPAD, LCC)
	Harvest	Combine	By hand or small combine
Heterogeneous treatment according to variation within a single field (continuously varying or patch-specific application)	Soil tillage (depth)	Compaction map-appl. map-VRT[a]	???[b]
	Land leveling	Laser leveling	Laser leveling
	Sowing rate/ planting density	Hydrology map-appl. map-VRT	???, patch-specific variation possible
	Liming	Soil pH map-appl. map-VRT	???
	Basal fertilizer application	Soil NPK map-appl. map-VRT	???, patch-specific variation possible
	Topdressed fertilizer application	Soil N map-appl. map-VRT, or real-time soil or plant sensor-VRT	???, SPAD, LCC could be used for patch-specific application
	Weed control	Weed sensor coupled with VRT or patch-specific herbicide application	Patch-specific hand-weeding/ herbicide application
	Pesticide applications	Real-time damage sensor-VRT	IPM monitoring, patch-specific variation possible based on observation
	Yield monitoring	Combine harvesters with GPS and yield monitor	???, small combine harvesters with GPS and yield monitor not yet used

[a] VRT = variable-rate technology. GPS = global positioning systems, SPAD = soil-plant analysis development, LCC = leaf color chart.

[b] ??? =currently not done.

information interpretation) combined with (3) understanding and availability of management options based on farmers' natural resource base (action options). This may well be a more knowledge-intensive exercise, relative to larger scale applications, because it is likely that at a larger scale there will be more service in the form of private sector input and more prepackaged options.

Going through a set of principal farm operations in irrigated rice cultivation, the important questions are: (1) How can it be done? and (2) Who could do it (farmer, contractor, government)? Table 1 summarizes some of the options for site-specific crop management in rice fields.

Regional SSCM decisions

How? Even in an SSCM approach, recommendations and decisions at regional scales play a role. At scales such as a district, province, or country, important agronomic advice can be given to farmers. Information captured may include (1) information about most suitable varieties for a given environment, (2) general recommendations for soil fertility management based on delineation of soil types, (3) weather forecasting and real-time seasonal variation in weather, and (4) pest forecasting and seasonal variation in pest populations. This would help farmers to make decisions about varieties, seedling age, planting date, fertilizer application, pest management, and harvest time. The major tools involved in this are remote sensing (e.g., high-resolution radar images), geographic information systems (GIS), crop models (Matthews et a1 1997, Singh et a1 1991), and pest models (Kropff et a1 1995, Pinnschmidt et al 1994). Mass media (TV, radio, newspapers) and extension systems are the main information providers.

Who? Government agencies have to provide this "regional technology" so that it can be used by all farmers, regardless of their socioeconomic differences and without imposing additional costs on them.

Variety selection

How? Most rice farmers select their varieties based on knowledge about adoption to site characteristics and agronomic fitness. Most modem varieties released are resistant to some common pests and are also screened for adaptation to soil stresses such as severe P and Zn deficiency or Fe toxicity. There is probably some scope for refining selection of varieties in an SSCM approach for (1) fitness for dry or wet seeding, (2) resistance to pests, (3) nutrient requirements, (4) grain quality, and (5) seed health. In nutrient requirements, better knowledge about the capacity for external nutrient acquisition at different growth stages and information about internal nutrient use efficiency would help in designing balanced fertilization schemes with a high synchronicity for supply and crop demand. This appears to be particularly important in the case of hybrids relative to other modem varieties.

Who? More variety-specific information should be jointly established by breeders, agronomists, plant protection specialists, and postproduction specialists (e.g., millers) and released through the national seed distribution and extension systems. Crop consultants may also play a role in providing this information as part of a more complex SSCM service to farmers.

Land preparation

How? SSCM options for land preparation vary widely. In many small to medium-size farms of Asia, the lowest feasible TAD for plowing with a 4-wheel tractor is a whole field, is., plowing depth would be uniform. Examples of field-specific SSCM decisions include (1) Is there need for plowing and puddling in each rice crop?, (2) Is there need for occasional deep plowing?, or (3) Is precision leveling feasible? During the past 20 years, many farmers have switched to shallow tillage machinery such as hydrotillers. This may lead to formation of shallow plow pans and a reduction in the rooted layer. Sporadic deep tillage to break hardpans and facilitate better root growth and soil percolation is another promising strategy, particularly in rice-nonrice systems (Kundu et al 1996, Yadav et a1 1996).

There is much scope for using laser-guided equipment for precision leveling even within small rice fields in direct-seeded areas. Laser leveling has been used in large rice farms in the US, Southern Russia, and Australia for many years, but the equipment is also available for leveling small fields of only about 0.2-ha size (Spectra Precision 1997). The depth of the leveling instrument would vary continuously according to a prescribed cut and fill map so that surfaces with no, unidirectional, or bidirectional slope can be precisely created. This technology offers new opportunities for direct dry and wet seeding because in precisely leveled fields water management is much more uniform so that crop emergence, weed control, snail control, and nutrient management can be much improved. Other options for site-specific soil tillage could be decisions in which fields and which cropping seasons minimum or even zero tillage can be used. Tools and rules for making SSCM decisions about soil tillage need further development.

Who? Presumably, options for site-specific tillage are mostly of interest for managing variability between and within fields in type II and III farms (see earlier). Direct-seeding areas are a primary target area and most of the operations would be contracted out to specialized companies.

Crop establishment

How? Two types of site-specific crop establishment decisions and operations are important: (1) assess whether a (whole) field is suited for a particular crop establishment method, and (2) vary sowing rates or transplanting density according to variation in soil properties and microrelief within a field. Decisions about suitability of a specific crop establishment technology and varying the sowing rate require expert knowledge and basic soil and climatic information. If this information is available, farmers could do field-specific or spot-based variation within a field in either sowing/planting by hand or modified mechanical transplanters or row seeders that allow easy adjustment on the go. For large farms, drill seeders with VRT features are available and can be modified for use in dry-seeded rice.

Who? Although many farmers will follow their own judgment, a more quantitative approach is warranted, which would probably be under the responsibility of the extension service or, if they exist, crop consultants. Access to specialized equipment will likely be through contractors.

Water management

How? Site-specific water management is closely linked with technologies available for soil tillage (e.g., puddling requirements). In particular, precise leveling is the most important factor in efficient irrigation management (Hill et a1 1991), but it would also reduce variability in weed growth, soil properties, and rice growth caused by heterogeneous water flow patterns within fields (Dobermann et a1 1997a). Various kinds of reduced irrigation, including reduced water depth, periodical flush irrigation, or sprinkler irrigation are options, but in most of them a single field would be treated homogeneously. Bypass flow in cracking clays may cause huge unproductive water losses during land soaking, i.e., during initial irrigation flush to achieve water saturation (Tuong et a1 1996). Dry shallow tillage soon after harvesting reduces soil drying and cracking during the fallow period and water need for the subsequent rice crop. In SSCM, soils and fields where this may be beneficial need to be identified. The same relates to decisions about need and type of drainage.

Who? The primary focus is on capture of suitable field- or farm-specific information to make a decision about the most appropriate water management technology. At this stage, we do not know who would be the best choice for this. Shallow tillage of dry soil requires high-powered tractors (preferably 4-wheel) so that this option appears restricted to type II and type III farms with somewhat larger field sizes.

Fertilizer application

How? Site-specific nutrient management in rice requires more quantitative information such as soil tests, leaf N monitoring, and accurate measurements of yields and externally provided nutrient inputs (Dobermann et a1 1996). Therefore, in type I or type II farms it will probably focus on managing between-field spatial variability and temporal variability occurring within 1 yr or growing season. Only in large type III farms can flexible, smaller VRT with application maps (e.g., tractors with disk spreaders) be used if sufficient information is generated. The situation may further improve once equipment with on-the-go sensors becomes fully developed. However, much of this technology exists for preplant or dry field conditions (Appendix 2). Suitable mechanized VRT for application in paddies during the cropping season is still scarce.

In most rice farms, a fertilizer recommendation is probably available only for a single (whole) field or farm or even larger areas. Field-specific decisions about fertilizer rates, types, splits, and application technology are required. However, farmers can easily vary N rates according to observation of actual plant N status by spot application of N fertilizer, i.e., manage within-field variability.

Tools for accurate, affordable field monitoring, data storage, and decision making play a pivotal role in site-specific fertilizer management, and many of them are already available. Examples include mobile soil testing laboratories used in Tamil Nadu, quick soil test kits, dynamic soil tests for in situ nutrient extraction (Dobermann et a1 1997c), chlorophyll meter or green leaf color charts for assessing plant N status (Peng et a1 1996), simple N-management crop models (ten Berge et a1 1997), and nutrient decision-support systems for specifying fertilizer recommendations (Dobermann et a1 1996). Over the shorter term, readily available soil information such as maps, local “soft” knowledge, or simple agronomic soil classification systems may be used to improve fertilizer recommendations at village or district scales.

Who? The huge number of single management units (field, parcel) that must be handled and the demand for quantitative information (e.g., soil testing) create physical limitations. Currently, it seems difficult to conduct soil testing or regular plant monitoring on a field-specific basis or, if done so, their costs per hectare may become too high. In most regions, the demand for service would easily exceed current facilities and the extension systems are inadequate to handle site-specific nutrient management. Training of farmers in information capture (tools) will be required, but government and private agencies will have to play the major role in information capture and processing. Farmers will likely be the ones applying the tools.

Pest management

How? Field-specific decisions may be based on both qualitative and quantitative information. There are three major agronomic options for site-specific management of weeds, insects, diseases, and other pests and they are applicable to all farm types:

- control via combination with other SSCM measures
- homogeneous, prophylactic control (spray the whole field)
- variable rate control based on observation or sensing (spray only on hot spots)

Hand-held sprayers dominate in pesticide applications, and improvements in their design allow more accurate and variable adjustment of rates during field operation. The heavy machinery (or even aircraft) used for variable rate application of pesticides in regions such as North America is only of interest to a few large type III farms.

Precision leveling allows precise water management as one important measure for field-specific weed control, particularly in direct-seeded rice (Williams et a1 1990). Weeds, particularly annual species, tend to occur in patches (Baki 1993) so that spot applications or variable rates of herbicides are feasible even when farmers use hand-held sprayers. Identification of suitable post-emergence herbicides will be required for this approach.

Ecologically sound site-specific pest management includes measures such as selection of resistant varieties, reduction in amount of pesticides used, substitution of less hazardous chemicals for more hazardous ones, and use of pesticides or nonchemical control measures based on knowledge of pest pressure. Following an IPM concept, application of insecticides could be restricted to spots with high infestation only, i.e., farmers would use a TAD of much smaller size to manage within-field variation with simple means (Fig. 2). With farm yields in tropical Asia expected to rise to 7-8 t ha^{-1} and more, we will see an increasing need for disease control using fungicides, cultural practices, or improved host-plant resistance (Heong et al 1995). Presumably, most of these are prophylactic measures applied to whole fields with less scope for managing variability within a field.

Who? Unlike in fertilizer management, much of the information required can be captured by observation so that site-specific pest management would mainly be the responsibility of farmers or farm managers. Training to improve farmers' knowledge about capturing information and translating it into application decisions plays a vital role.

Postproduction—harvest and on

How? SSCM can be interpreted in various ways after harvest. First, yield maps such as those being developed automatically by yield monitors (such as in the US, etc.) can be used as guides to refine management both of fields and within a field. They can be used to identify management effects (e.g., variety, fertilizer, rotation, etc.) on yields, and so management can be refined. While yield monitors are not expected to be common except in a few type III farms, good record keeping of yields on a field- or parcel-specific basis could be used to provide such management guidance in small farms.

The second aspect relates to maximizing returns during postproduction. While farmers can see their yield, many of the subsequent effects of their harvest and losses are unseen.

For example, variety, harvest date, and postproduction management (e.g., drying, storage) can have large effects on head rice yields and quality (e.g., discoloration). These factors are essentially hidden from farmers, who will likely lose interest once the grain leaves their farm gate. However, as premiums for quality (taste and head rice yields) become important, they will strive for improvement in postproduction systems and add incentives (if credit systems allow) to maximize the added value of their crops. A major consideration in this is the method of harvest and handling. The major SSCM aspect is, therefore, variety selection and timely (i.e., optimum moisture content) harvest.

Although options for by-product use (e.g., hulls, straw) are generally known, they will require system (total farm) management. For example, straw removal (e.g., integrated animal systems, mushroom production) will require fertilizer substitution and straw enrichment for animals.

Who? Farmers will need greater information on variety effects on quality and effects of harvest time (grain moisture content) and by-product use options. This will require training to improve farmers' knowledge and incentives for the multiple players in the postproduction chain. Mechanized harvest will likely be done by contractors.

Present primary needs

SSCM or precision farming is an emerging, not a mature, management system. As such, there are a number of research and verification requirements. We summarize some of these below (ASAE 1997):

1. Knowledge capture: Identify and quantify (map) the variability of key input parameters at the scale needed to make a decision about the specific SSCM operation.
   - Clarify information to monitor the different scales of production.
   - Identify suitable tools to quantify variation in key information at different production scales.
   - Identify appropriate sensors (more for large-scale VRT).

2. Knowledge interpretation: Translate the information into decisions about management (application) by understanding sources of variability and their impact on yield.
   - Validate response functions to identify optimum management for the range of soil and climatic conditions encountered.
   - Identify what tools are available/needed for information to be interpreted.
   - Identify appropriate crop management options for the different production scales.
   - Improve analysis tools for interpreting yield maps and effects of management decisions.
   - Improve model simulation to predict management effects and on-the-go management options.
   - Improve record keeping for data storage, retrieval, and interpretation.

3. Application: Identify available application technology and optimal size of technology application domain. Apply differential amounts of inputs to the TADs.
   - What technologies are available/needed to apply the treatment?
   - How can the whole approach be communicated and implemented?

4. Communication: Identify who will pass the message and how.
   - Identify improved communication channels to facilitate transfer of precision farming concepts at all levels of resource and production. This has implications for the public (research and extension) and private sectors (dealers and contractors).
   - Identify the effect of changing demographics of farming (e.g., increasing age?).

5. General
   - Identify incentives to adopt technologies.
   - Build in environmental concerns.
   - Ensure compatibility of different system components (primarily for large-scale VRT).
   - Document benefits.

Summary

Historically, institutes such as IRRI have focused on providing global solutions (package approach) based on strategic research, with the local solutions being the responsibility of the NARS (research and extension). This transfer process has not always worked well and at times the science developed has not reached the farmer.

We believe that the components now exist to move from a regional approach to resource management recommendations to the farm- or even field-specific level (i.e., SSCM). This has to include land preparation, crop establishment, water management, pest management, and nutrient management plus all their interactions as the basic components. Such SSCM will help increase production and profitability while protecting the environment. The new system will, however, come with new demands in management and extension expertise. Thus, if the traditional research-extension model had problems, we can expect the system to be even more heavily "taxed" with requirements of a more knowledge-intensive system. In addition to the scientific work required, we have to identify what system will best accommodate the needed changes in information/knowledge transfer and whether new agents of change need to be included in the approach.

In countries where SSCM has evolved, the technology is advancing fast, but the theoretical work has lagged behind. Development of sound procedures for information collection and accurate decision making is insufficient and the long-term biophysical and economic benefits of SSCM remain to be demonstrated. Further, many of the input response functions still have to be verified under a range of conditions. Nevertheless, we believe that the concept of SSCM is right and that many of the initial difficulties can be overcome as the technologies develop.

In China, SSCM may provide the basis for sustaining high rice yields in the coastal regions as well as achieving substantial yield increases in the central and western parts of the country where yields are lower. We believe that SSCM can lead to substantial improvements in input use efficiency (i.e., product/unit input). One important opportunity will be to design integrated farms (e.g., rice-animal) where rice by-product use (e.g., straw) is examined in terms of the optimal flows of nutrients, water, energy, and labor at the whole farm level.

SSCM aims at integrating the knowledge generated by various scientific disciplines into more complex but site-specific guidelines for action at the farm level. The principles of precision farming or SSCM are applicable to farms and fields of any size, including those found in Asia, but the specific technological solutions differ from case to case.

Acknowledgments

Data on socioeconomic farm characteristics (Appendix 3) were collected by researchers from India, Indonesia, the Philippines, Thailand, and Vietnam participating in the Reversing Trends of Declining Productivity (RTDP) project.

References

Ag-Chem. 1997. Site-specific handbook. 5th ed. Minnetonka, MN: Ag-Chem Equipment Co., Inc.

Angus JF, St.-Groth CF, Tasic RC. 1990. Between-farm variability in yield responses to inputs of fertilizers and herbicide applied to rainfed lowland rice in the Philippines. Agric. Ecosyst. Environ. 30:219-234.

ASAE, editor. 1997. Precision agriculture. A position statement by ASAE. St. Joseph, MN.

Baki BB. 1993. Spatial pattern analysis of weeds in selected rice fields of Samarahan, Sarawak. MARDI Res. J. 21(2):121-128.

Beckett PHT. 1987. Spatial variability of soil K-status. In: Methodology in soil-K research. Bern: International Potash Institute. p 357-380.

Beckett PHT, Webster R. 1971. Soil variability: a review. Soils Fert. 34: 1-1 5.

Borgelt SC. 1993. Sensing and measurement technologies for site-specific management. In: Soil specific crop management. A workshop on research and development issues. Robert PC, Rust RH, Larson WE, editors. Madison, WI: ASA, CSSA, SSSA. p 141-157.

Burgess TM, Webster R. 1980. Optimal interpolation and isarithmic mapping of soil properties. I. The semi-variogram and punctual kriging. J. Soil Sci. 31 :315-331.

Burrough PA. 1993. Soil variability: a late 20th century view. Soils Fert. 56:529-562.

Byerlee D. 1996. Knowledge-intensive crop management technologies: concepts, impacts and prospects in Asian agriculture. In: Paper presented at the International Rice Research Conference, 3-5 June, Bangkok, Thailand.

Cassman KG, Dobermann A, Sta. Cruz PC, Gines GC, Samson MI, Descalsota JP, Alcantara JM, Dizon MA, Olk DC. 1996. Soil organic matter and the indigenous nitrogen supply of intensive irrigated rice systems in the tropics. Plant Soil 182:267-278.

Cassman KG, Peng S, Dobermann A. 1997. Nutritional physiology of the rice plant and productivity decline of irrigated lowland rice systems in the tropics. In: Plant nutrition — forsustainable food production and environment. Ando T, Fujita K, Mae T, Matsumoto H, Mori S, Sekiya J, editors. Tokyo: Kluwer Academic Publishers. p 783-788.

Cassman KG, Pingali P. 1995. Intensification of imgated rice systems: Learning from the past to meet future challenges. GeoJournal 35:299-305.

Chancellor WJ, Goronea MA. 1994. Effects of spatial variability of nitrogen, moisture, and weeds on the advantages of site-specific applications for wheat. Trans ASAE. 37:717-724.

Deere and Company. 1997. The precision farming guide for agriculturists. An agricultural primer. Moline, IL: Deere and Company.

Dessaint F, Caussanel JP. 1994. Trend surface analysis — Asimple tool for modeling spatial patterns of weeds. Crop Prot. 13:433-438.

Dobermann A. 1994. Factors causing field variation of direct-seeded flooded rice. Geoderma 62: 125- 150.

Dobermann A, Cassman KG, Peng S, Pham Sy Tan, Cao Van Phung, Sta. Cruz PC, Bajita JB, Adviento MAA, Olk DC. 1996. Precision nutrient management in intensive irrigated rice systems. In: Proceedings of the International Symposium on Maximizing Sustainable Rice Yields Through Improved Soil and Environmental Management, 11-17 November, Khon Kaen, Thailand. Dept. of Agriculture, Soil and Fertilizer Society of Thailand, Dept. of Land Development, ISSS, Bangkok. p 133-154.

Dobermann A, Gaunt JL, Neue HU, Grant IF, Adviento MAA, Pampolino MF. 1994. Spatial and temporal variability of ammonium in flooded ricefields. Soil Sci. Soc. Am. J. 58:1708-1717.

Dobermann A, Goovaerts P, Neue HU. 1997a. Scale dependent correlations among soil properties in two tropical lowland rice fields. Soil Sci. Soc. Am. J. 61:1483-1496.

Dobermann A, Oberthuer T. 1997. Fuzzy mapping of soil fertility — a case study on irrigated riceland in the Philippines. Geoderma 77:317-339.

Dobermann A, Pampolino MF, Adviento MAA. 1997b. Resin capsules for on-site assessment of soil nutrient supply in lowland rice fields. Soil Sci. Soc. Am. J. 61:1202-1213.

Dobermann A, Pampolino MF, Neue HU. 1995. Spatial and temporal variation of transplanted rice at the field scale. Agron. J. 87:712-720.

Donald WW. 1994. Geostatistics for mapping weeds, with a Canada Thistle (*Cirsium arvense*) patch as a case study. Weed Sci. 42:648-657.

Felton WL, Doss AF, Nash PG, McCloy KR. 1991. A microprocessor controlled technology to selectively spot spray weeds. In: Automated agriculture for the 21st century: proceedings of the 1991 symposium. ASAE, editor. Michigan: ASAE. p 427-432.

Gravois KA, Helms RS. 1994. Effect of uneven emergence on rice yield, milling yield, and yield components. Aust. J. Exp. Agr. 34:949-952.

Haynes WB, Keen BA. 1925. Studies on soil cultivation. II. A test of soil uniformity by means of dynamometer and plough. J. Agric. Sci. 15:387-394.

Heong KL, Teng PS, Moody K. 1995. Managing rice pests with less chemicals. GeoJournal 35:337-349.

Heuvelink GBM. 1993. Error propagation in quantitative spatial modeling applications in geographical information systems. PhD thesis. University of Utrecht.

Hill JE, Bayer DE, Bocchi S, Clampett WS. 1991. Direct seeded rice in the temperate climates of Australia, Italy and the United States. In: Direct seeded flooded rice in the tropics. IRRI, editor. Los Baños, Philippines: IRRI. p 91-102.

Hoosbeek MR, Bryant RB. 1992. Towards the quantitative modeling of pedogenesis — a review. Geoderma 55:181-210,

Huang C-H, Bradford JM. 1992. Application of a laser scanner to quantify soil microtopography. Soil Sci. Soc. Am. J. 56:14-21.

Hubbard KG. 1994. Spatial variability of daily weather variables in the high plains of the USA. Agric. Forest. Meteorol. 68:29-41.

Kropff MJ, Teng PS, Rabbinge R. 1995. The challenge of linking pest and crop models. Agric. Syst. 49(4):413-434.

Kundu DK, Ladha JK, Lapitan-de Guzman E. 1996. Tillage depth influence on soil nitrogen distribution and availability in a rice lowland. Soil Sci. Soc. Am. J. 60:1153-1159.

Lannou C, Savary S. 1991. The spatial structure of spontaneous epidemics of different diseases in a groundnut plot. Neth. J. Plant Pathol. 97:355-368.

Larkin RP, Gumpertz ML, Ristaino JB. 1995. Geostatistical analysis of *Phytophthora* epidemic development in commercial bell pepper fields. Phytopathology 85:191-203.

Leenhardt D. 1995. Errors in the estimation of soil water properties and their propagation through a hydrological model. Soil Use Manag. 11 : 15-21.

Matthews RB, kopff MJ, Horie T, Bachelet D. 1997. Simulating the impact of climate change on rice production in Asia and evaluating options for adoption. Agric. Syst. 54:399-425.

McBratney AB. 1985. The role of geostatistics in the design and analysis of field experiments with reference to the effect of soil properties on crop yield. In: Soil spatial variability. Nielsen DR, Bouma J, editors. Pudoc, Wageningen. p 3-8.

McBratney AB, Whelan BM. 1995. The potential for site-specific management of cotton farming systems. CRC for Sustainable Cotton Production. Narrabi, NSW.

Miller DM. 1990. Variability of soil chemical properties and rice growth following land levelling. Ark. Farm Res. 39:4.

Mortensen DA, Johnson GA, Wyse DY, Martin AR. 1995. Managing spatially variable weed populations. In: Site-specific management for agricultural systems. Robert PC, Rust RH, Larson WE, editors. Madison, WI: ASA, CSSA, SSSA. p 397-415.

Moya P, Pabale D, Pingali PL. 1997. Reversing the yield decline in intensively cultivated irrigated rice lands: preliminary report on farmer performance and socioeconomic monitoring. SSD discussion paper. Los Baños, Philippines: IRRI.

Oberthuer T, Dobermann A, Neue HU. 1996. How good is a reconnaissance soil map for agronomic purposes? Soil Use Manag. 12:33-43.

Olk DC, Cassman KG, Simbahan G, Sta. Cruz PC, Abdulrachman S, Nagarajan R, Pham Sy Tan, Satawathananont S. 1996. Congruence of N fertilizer management by farmers and soil N supply in tropical irrigated lowland rice systems. In: Proceedings of the international symposium on maximizing sustainable rice yields through improved soil and environmental management, 11 - 17 November, Khon Kaen, Thailand. Dept. of Agriculture, Soil and Fertilizer Society of Thailand, Dept. of Land Development, ISSS, Bangkok. p 29-38.

Or D, Hanks RJ. 1992. Soil water and crop yield spatial variability induced by irrigation nonuniformity. Soil Sci. Soc. Am. J. 56:226-233.

Palmer RJ. 1995. Positioning aspects of site-specific applications. In: Robert PC, Rust RH, Larson WE, editors. Site-specific management for agricultural systems. Madison, WI: ASA, CSSA, SSSA. p 613-618.

Peng S, Garcia FV, Laza RC, Sanico AL, Visperas RM, Cassman KG. 1996. Increased N-use efficiency using a chlorophyll meter on high-yielding irrigated rice. Field Crops Res. 47:243-252.

Pinnschmidt HO, Long ND, Mekwatanakarn P, Viet lT, Don LD, Teng PS, Dobermann A. 1994. Relationships between soil properties, crop and pest management practices, pest intensity, and crop performance in rainfed lowland rice. Int. Rice Res. Notes 19:23-25.

Reetz HF Jr., Fixen PE. 1995. Economic analysis of site-specific nutrient management systems. In: Robert PC, Rust RH, Larson WE, editors. Site-specific management for agricultural systems. Madison, WI: ASA, CSSA, SSSA. p 743-752.

Robert PC, Rust RH, Larson WE, editors. 1993. Soil specific crop management: a workshop on research and development issues. 14-16 April 1992, Minneapolis, MN and Madison, WI: ASA, CSSA, SSSA.

Robert PC, Rust RH, Larson WE, editors. 1995a. Preface. In: Site-specific management for agricultural systems. Madison, WI: ASA, CSSA, SSSA. p xiii-xiv.

Robert PC, Rust RH, Larson WE, editors. 1995b. Site-specific management for agricultural systems. Madison, WI: ASA, CSSA, SSSA.

Schueller JK. 1992. A review and integrating analysis of spatially variable control of crop production. Fert. Res. 33:l-34.

Schueller JK. 1997. Technology for precision farming. In: Precision agriculture '97. Proceedings of the First European Conference on Precision Agriculture, 7-10 September, Coventry, U.K. Stafford JV, editor. Coventry. p 33-44.

Schueller JK, Wang M. 1994. Spatially variable fertilizer and pesticide application with GPS and DGPS. Computers Electronics Agric. 11 :69-83.

Searcy SW. 1995. Engineering systems for site-specific management: opportunities and limits. In: Robert PC, Rust RH, Larson WE, editors. Site-specific management for agricultural systems. Madison, WI: ASA, CSSA, SSSA. p 603-612.

Singh U, Ritchie JT, Godwin DC. 1991. A user's guide to CERES-RICE - V2.10. Muscle Shoals, AL, IFDC.

Spectra Precision. 1997. Precision land leveling; concept and benefits. Dayton, Ohio: Spectra Precision.

ten Berge HFM, Thiyagarajan TM, Quinghua Shi, Wopereis MCS, Drenth H, Jansen MJW. 1997. Numerical optimization of nitrogen application to rice. Part I. Description of MANAGE-N. Field Crops Res. 51:29-42.

Tuong TP, Cabangon RJ, Wopereis MCS. 1996. Quantifying flow processes during land soaking of cracked rice soils. Soil Sci. Soc. Am. J. 60:872-879.

Tyler DA. 1993. Positioning technology (GPS). In: Robert PC, Rust RH, Larson WE, editors. Soil specific crop management. A workshop on research and development issues. Madison, WI: ASA, CSSA, SSSA. p 159-165.

Ueno M, Sato Y, Otake T. 1988. Analysis of the effect of soil nitrogen efficiency on nitrogen nutrition diagnosis in rice. 4. Mapping of soil nitrogen mineralization and estimation of the effect of climate on soil inorganic nitrogen level. Agric. Hortic. 63: 1389-1393.

Webster R. 1985. Quantitative spatial analysis of soil in the field. Adv. Soil Sci. 3:l-70.

Webster R, Boag BA. 1992. Geostatistical analysis of cyst nematodes in soil. J. Soil Sci. 43:583-595.

Webster R, McBratney AB. 1987. Mapping soil fertility at Broom's Barn by simple kriging. J. Sci. Food Agric. 38:97-115.

Williams JF, Roberts SR, Hill JE, Scardaci SC, Tibbi. 1990. Managing water for weed control in rice. California Agric. 44:7-10.

Woebbecke DM, Meyer GE, Vonbargen K, Mortensen DA. 1995. Color indices for weed identification under various soil, residue, and lighting conditions. Trans. ASAE 38:259-269.

Wollenhaupt NC, Buchholz DD. 1993. Profitability of farming by soils. In: Soil specific crop management: a workshop on research and development issues. Robert PC, Rust RH, Larson WE, editors. Madison, WI: ASA, CSSA, SSSA. p 199-211.

Yadav RL, Prasad K, Dwivedi BS, Chandra D, Yadav DS, Jha KP. 1996. Resource dynamics and management in rice-based cropping systems. In a paper presented at the India-IRRI Dialogue, 27-29 September, 1996, ICAR, IRRI, Delhi.

Appendix 1
Currently used definitions

Terms such as precision agriculture, precision farming, prescription farming, site-specific farming, site-specific crop management, soil-specific crop management, farming by soil, local resources management, or knowledge-intensive management are used to describe modem farming concepts that try to find a profitable and sustainable balance between agricultural food production and quality of land and water resources by using more and better knowledge. Some definitions include:

- *"Site-specific crop management* (SSCM) is an information and technology-based agricultural management system to identify, analyze, and manage site-soil spatial and temporal variability within fields for optimum profitability, sustainability, and protection of the environment" (Robert et al 1995a).
- *"Site-specific crop management* is the use of local soil and crop parameters to make precise applications of production inputs to small areas with similar characteristics" (Searcy 1995).
- *"Precision farming* involves collecting and managing information to make practical, economical, and environmentally sound crop production decisions. Site-specific farming embodies the practice of applying crop inputs in each part of a field according to its unique set of conditions..." (Ag-Chem 1997).
- *Precision farming* ..."To optimize the use of soil and water resources and chemical inputs (fertilizers and pesticides) on a site-specific basis." Such management improves farm profitability and protects the environment. (From: "Optimizing Management for Precision Farming: A Systems Approach," Training Program, Gainesville, University of Florida.)
- *Precision farming* "means managing each crop production input — fertilizer,limestone, herbicide, insecticide, seed, etc.—on a site-specific basis to reduce waste, increase profits, and maintain the quality of the environment" (Deere and Company 1997).
- "The basic concept of precision agriculture is to match inputs and practices to localized conditions within a field to do the right thing, in the right place, at the right time, and in the right way" (ASAE 1997).

Appendix 2
SSCM technologies for managing variability in large fields

Real-time positioning systems

Global positioning systems (GPS) and local triangulation between multiple beacons are the two principal technologies for achieving precise positioning of machinery in the field. GPS receivers mounted on equipment (tractor, combine, other equipment) receive signals from a number of geostationary satellites launched by various countries. With differential GPS systems, accuracy of 5 m or less is now a reality and usually sufficient for varying the rate of an application to match conditions in the field (Palmer 1995, Tyler 1993). Sophisticated radio frequency systems such as the Accutrak System allow accuracies in the order of 15 cm and can be used for driving guidance systems (Palmer 1995).

GPS receivers have become very affordable and positioning technology has advanced very fast during the past few years. It is hardly a limiting factor in current SSCM approaches.

On-the-go sensors

Development of on-the-go sensors has focused on yield monitors attached to combines and other harvest equipment. This technology is now very well established and has become affordable for many farmers in North America and other regions. In the United States, about 10,000 combines are already equipped with yield monitors and GPS (P. Fixen, PPI, personal communication) and intensive research continues to develop such devices for a wide variety of crops (Borgelt 1993). Most companies expect new combines to have such equipment as standard.

On the other hand, development of soil or crop sensors as a fundamental component of continuous information processing—application technologies (Fig. 3)-appears to have lagged behind. After some initial results much of this work was taken over by the industry and is now highly secretive. Examples include:

- Single or multiple wavelength sensors that project light into the soil and estimate soil organic matter content based on the energy reflected (e.g., S.M.A.R.T., Tyler, MN).
- The Soil Doctor (Crop Technologies, Inc.), a system tested since 1987. The different models have either rolling electrode systems or electrode-equipped sensor knives. According to the manufacturer, those sensors measure organic matter, soil moisture, and nitrate levels to prescribe and deliver fertilizer on-the-go (Borgelt 1993), but details about the accuracy and performance are not well known.
- Ion selective electrodes or field effect transistors (ISFET) to measure soil nitrate (Borgelt 1993).
- Remote laser sensors for measuring chlorophyll content of plants. Norsk Hydro has recently developed a device that is mounted on the front of a tractor and scans the canopy for chlorophyll content on the go. At the same time, the rate of N application is continuously adjusted to those readings (J. Wollring, Norsk Hydro, personal communication).
- Color index or reflectance-based weed detection sensors (Felton et a1 1991, Woebbecke et a1 1995).

So far, none of these technologies seems to be in widespread use, but the industry puts much effort into their development. The lack of continuous, mobile devices for sensing soil chemical properties is a major factor limiting the adoption of SSCM (Schueller 1992).

Processing and storage of digital data
When a field is managed as a collection of distinct smaller areas, the number of management decisions is greatly increased. In many cases, farmers will rely on consultants to help implement SSCM (Searcy 1995). Software and hardware needed includes facilities for image processing, geographical information systems, statistical analysis, models for decision making, and graphic displays.

Many products are available. However, most so-called decision support systems (DSS) for SSCM are limited to a rather simple combination of data layers in a GIs. Some of the problems associated with this are discussed below.

Variable-rate technology

The ability to vary application rates while traveling through a field is critical to the SSCM concept. Besides the tremendous advances in positioning systems and computer technology, VRT equipment is probably the best-developed part of SSCM systems (Searcy 1995). The major manufacturers of agricultural equipment have stepped into the business of developing and manufacturing VRT for site-specific management. Depending on the specific SSCM system used (Fig. 3), VRT can be map-based (an application map controls the applicator) or sensor-based (a sensor controls the applicator in a closed-loop system).

Map-based applicators are available for a wide range of agronomic operations, including soil tillage, drill-seeding, or application of granular and liquid chemicals. Sensor-based VRT is not yet widely used (Searcy 1995), but may develop fast.

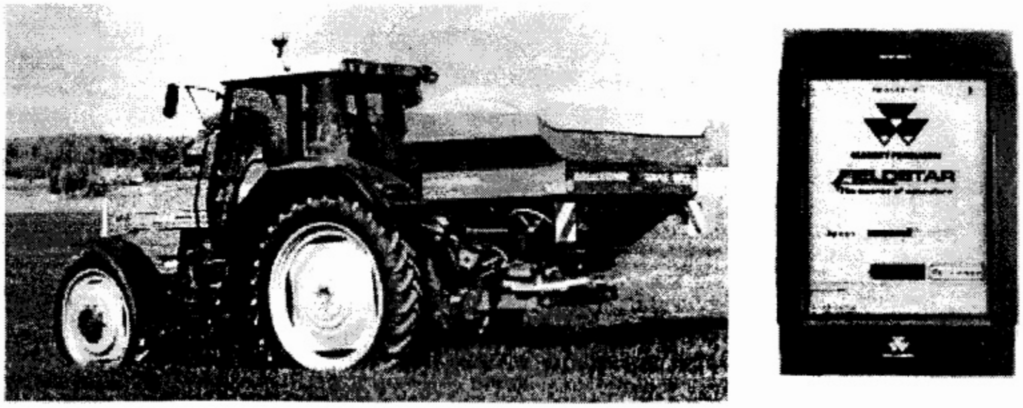
According to design and customer specification, we can distinguish between:

1. Modular designs with an open architecture. These are mostly modifications of conventional equipment in which some of the devices can be combined with different pieces of VRT. Such machinery is usually more flexible and affordable for smaller farmers who often have to switch from one operation to another.

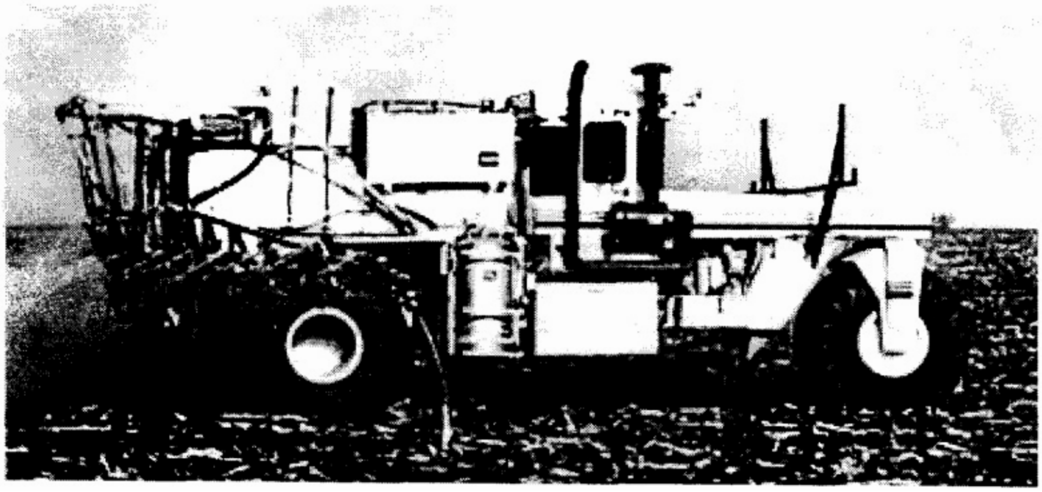
One example of this is the Massey Ferguson FIELDSTAR™ system, in which main components such as the GPS receiver and the Datavision terminal can be easily installed on different tractors or combines. The data terminal is used for storing all field information (application maps, yield maps) and controls specific equipment such as fertilizer spreader, plow, or drill seeder.

2. Highly specific machinery exclusively designed to perform one or a few specific tasks. This is usually large equipment developed for the custom application market and most suitable for managing large fields.

Perhaps the most impressive machine in this category is the Terra-Gator© 1903 with Soilection Twin Bin™ (Ag-Chem 1997). Powered by a 400-hp engine, it applies up to five chemicals (3 granular, 2 liquid) simultaneously in one go, with each chemical continuously varying based on five different field application maps fed into the controller. On a normal work day, this $200,000 machine applies fertilizers and other chemicals on 300 ha, provided the company operating it has enough transport capacity to truck all the fertilizers needed to the field fast enough. Another example is the big laser-guided carryall scraper used for precision leveling (Spectra Precision 1997).



Massey Ferguson FIELDSTAW™ with AMAZONE ZA-M MAX variable fertilizer spreader.



Terra-Gatoa 1903 with Soilection Twin Bin™.

Appendix 3
Characteristics of rice farms in Asia

Selected socioeconomic and performance characteristics of farms in major irrigated rice domains of South and Southeast Asia. Only average data for two cropping seasons with the highest yield potential (dry season) sampled between 1995 and 1996 are shown (based on Moya et al 1996).

	Central Plain Thailand	Central Luzon Philippines	Mekong Delta Vietnam	Tamil Nadu India	West Java Indonesia
No. of farms sampled	26	33	32	28	30
Total farm size (ha)	4.3	2.6	1.1	4.6	1.6
Area planted to rice (ha)	2.1	1.8	0.9	2.1	1.2
Age of household head (years)	46	50	47	46	42
Education (years in school)	5	7	7	10	7
Household size (no.)	5	6	6	6	4
Transplanting (% of area)[a]	0	16	0	100	100
Wet-seeding (% of area)	100	76	100	0	0
Rice yield (t ha^{-1})[b]	4.6	6.4	5.4	6.4	5.5
Total revenue (US$ ha^{-1})	821	2018	847	663	1351
Total costs (US$ ha^{-1})	354	439	268	344	552
Net return (US$ ha^{-1})	467	1579	578	319	799
Factor shares (% of total revenue)					
Fertilizers	11.1	5.5	8.9	13.5	5.1
Pesticides	3.9	1.5	2.6	0.7	2.8
Other inputs"	5.3	5.5	6.2	5.1	4.6
Family labor	5.1	2.2	4.9	1.8	3.3
Hired labor	17.8	7.0	9.2	30.9	25.1
Net return[d]	56.8	78.3	68.2	48.0	59.1
Labor use (8 h person-day ha")					
Land preparation	3.3	9.9	11.7	12.9	20.2
Crop establishment	0.9	7.9	11.0	53.1	19.0
Crop care	4.5	3.9	12.2	99.8	32.0
Harvest/postharvest	6.7	27.9	29.3	44.2	24.3
Total	15.4	49.6	64.2	210.0	95.5
No. of fertilizer applications (%)					
One or two times per crop	42	62	20	0	100
Three or four times per crop	58	38	78	55	0
More than four times per crop	0	0	2	45	0
Pesticide use (kg ai ha^{-1})[e]					
Insecticide	0.84 (92)	0.26 (61)	0.59 (89)	0.51 (59)	0.81 (97)
Herbicide	0.80 (92)	0.39 (96)	0.27 (80)	0.06 (5)	0.87 (97)

[a] Some farmers in Central Luzon practiced both transplanting and wet-seeding so that the total is not 100.
[b] Average yield of two seasons measured by researchers in one farmer's field.
[c] Includes fuel, irrigation, and machine rental.
[d] Includes farmer's surplus and return to land.
[e] The number in parentheses shows the % of farmers using the pesticide.

Demand-supply balance in the world rice market: implications for China's food security strategy

Mahabub Hossain[1] and Jikun Huang[2]

[1] Social Sciences Division, International Rice Research Institute, MCPO Box 3127, 1271 Makati City, Philippines
[2] China Center for Agricultural Policy; Chinese Academy of Agricultural Sciences, Beijing, China

Asia has an impressive record of feeding an ever growing population with limited land resources. The Green Revolution contributed to a growth in staple grain production at nearly 3% per year over the last three decades, keeping pace with population growth and income growth-induced changes in per capita food consumption. Yet, despite improvements in food availability, poverty and food insecurity still exist in many low-income countries. Recent World Bank estimates indicate that nearly 1.1 billion people still live in poverty and 840 million suffer from hunger, 70% of them in Asia (World Bank 1992, Bender and Smith 1997).

Dramatic developments in Asian economies have been affecting the demand-supply balances of staple grains. Middle- and high-income countries have experienced a decline in per capita consumption of rice, the dominant food staple of Asia, because of changes in food habit associated with income growth and urbanization. Population growth will, however, remain a major force behind the substantial increase in total demand for staple grains for the next 30 to 50 years. Also, the demand for feed grains (mostly maize) will increase substantially as consumption of livestock products expands with further growth in per capita incomes. On the supply side, the prosperous Asian countries increasingly find it difficult to sustain producers' interest in rice farming. The move toward free trade in agricultural production, initiated by the Uruguay Round of the General Agreement on Tariffs and Trade (GATT), will further dampen incentives for rice farming in these countries. The potential for increased productivity created by the dramatic technological breakthrough in the late 1960s has almost been exploited, particularly for irrigated and favorable rainfed environments. So, without further technological advances, it will be difficult to maintain growth in rice production at historical rates.

As rice production loses the race against population, sustaining food security becomes a critically important concern for land-scarce, low-income countries. Affluent Asians could buy rice in the world market by offering higher prices, but the prospect of generating exportable surplus outside Asia is limited as 90% of rice is grown and consumed in the region. If rice supply fails to keep pace with demand, the price will increase and the market will reallocate scarce supplies from low-income to high-income consumers, which may aggravate poverty and food insecurity in low-income countries. Because poverty alleviation is a major political objective, governments in food-surplus countries may raise trade barriers to protect their domestic consumers, a reaction that may prevent affluent food-deficit countries from depending on the world market for food security.

The question is whether or not Asia will be able to sustain favorable food balances and further improve food security for low-income households. This paper analyzes the factors governing the demand-supply balances for rice in the world market, and examines the political factors that could affect the trade-off between pursuing self-sufficiency in domestic production and achieving self-reliance through trade in sustaining food security. Finally, it provides an overview of Chinese rice supply-demand balances and draws implications for China's rice production strategy.

Emerging trends in demand

The growth in demand for a staple grain depends on (a) population growth rate, (b) level and growth of per capita income, (c) urbanization and associated changes in food habits, and (d) changes in price relative to substitute food crops. At low income levels, when acquiring calories to sustain a healthy productive life is a serious concern, rice is considered a luxury commodity. With economic prosperity, people tend to replace low-cost sources of calories such as coarse grains, cassava, and sweet potato with rice. But when income reaches a threshold where energy needs of household members are already met, rice becomes an inferior good. As incomes rise further, consumers adopt a diversified diet and replace rice with a high-cost quality food with more protein and vitamins, such as vegetables, fruits, fish, and livestock products. Growing urbanization, which accompanies economic growth, also leads to changes in food habits, and the practice of eating outside the home further reduces per capita rice consumption.

Japan, South Korea, and Taiwan, China, have already passed through these phases and experienced a decline in per capita rice consumption after reaching a high level several decades earlier (see Fig. 1 for the Japanese experience). Recently, Malaysia, Thailand, and China have gone through the same experience. But, the income threshold at which consumers start trading rice for higher quality and more varied foods has not yet been reached in South Asia and the low-income countries of Southeast Asia. These countries account for more than 40% of global rice consumption. Per capita food grain consumption in these countries is still lower than the peak level reached in Korea and Japan during their early phase of development. With increased incomes and alleviation of poverty, these countries may soon experience an increase in per capita rice consumption.

The most important factor exerting upward pressure on rice demand will, however, be population growth. With growing economic

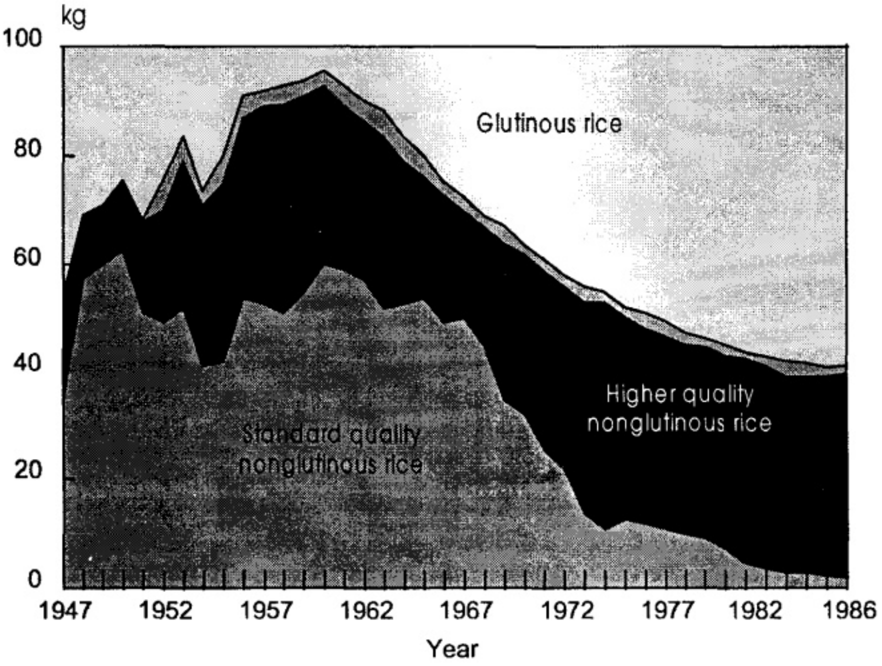


Fig. 1. Changes in rice consumption in Japanese nonfarm households (per capita annual data).
Source: Comprehensive Time Series Report on the Family Income and Expenditure Survey 1947-1986.

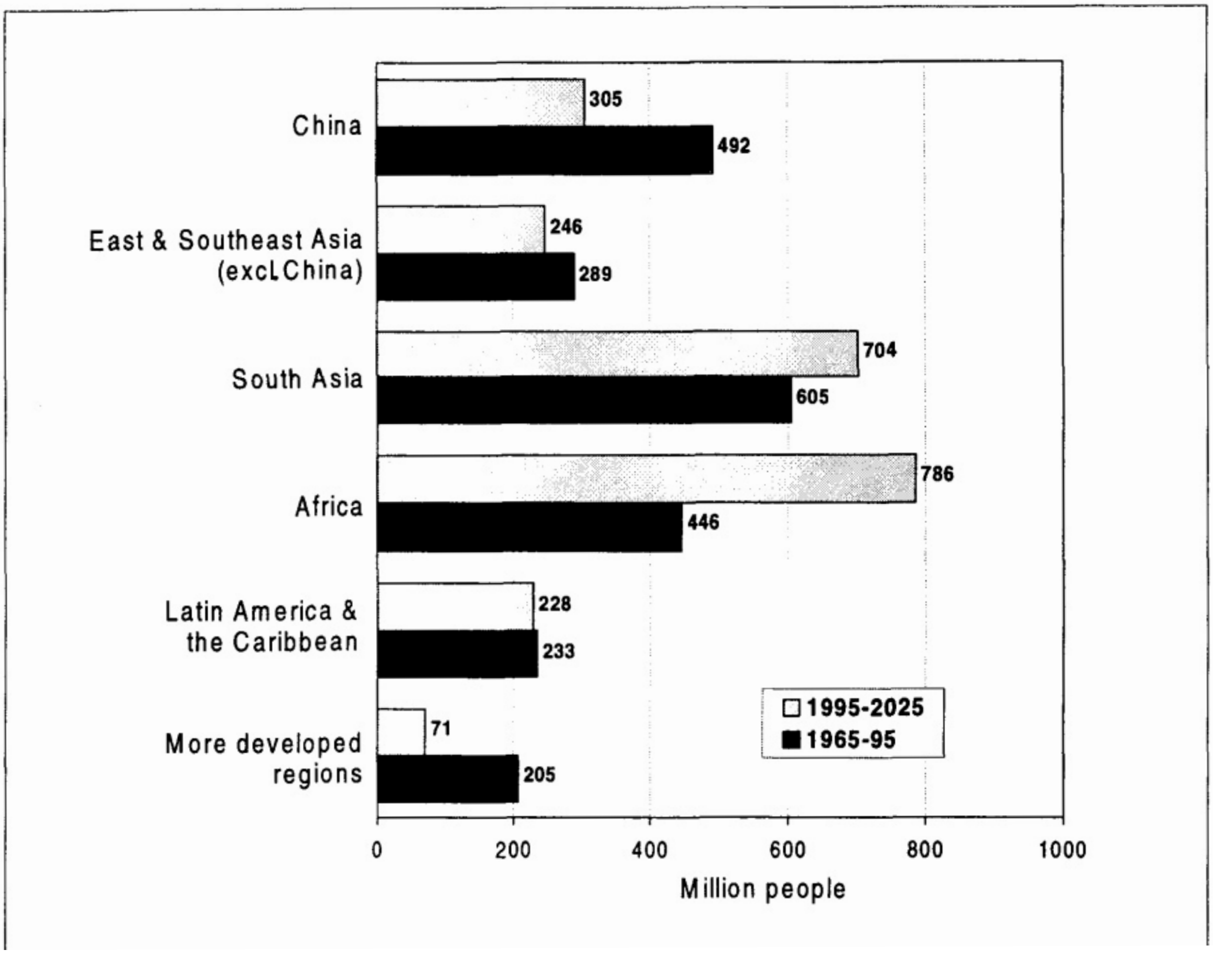


Fig. 2. Projected population increase in the next three decades compared with increase over the last three decades. Source: World Bank.

prosperity, population growth has also been declining in most rice-consuming Asian countries. According to UN projections, annual population growth in developing countries will decline from its present level of 1.9% to 1.1 % by 2025. Due to the expanded population base (from 4.5 billion in 1995 to 6.8 billion in 2025), however, the absolute increase in the number of people over the next three decades will remain as large as during the last three decades (Fig. 2). Ironically, it is in the poverty-stricken regions where per capita rice consumption is expected to increase that the population will also grow fastest. In South Asia, for example, the population is projected to increase by 704 million over the next three decades compared with 605 million over the previous three decades, whereas in East and Southeast Asia the absolute increase in number of people is going to decline.

Global food projections to 2020 recently made by the International Food Policy Research Institute (IFPRI) (Rosegrant, Sombilla, and Perez 1995) indicate that the demand for cereal grains will increase by 72% over 1990-2020 and that of rice by nearly 60%, most of it because we will be feeding a larger population. For low-income countries of South and Southeast Asia, rice demand may double within the next 40 years.

Emerging trends in supply

Two major factors may substantially affect rice production growth in the future. First, the prosperous Asian countries are finding it difficult to sustain producers' interest in rice farming. The move toward free trade in agricultural production, initiated by the recently concluded GATT, will have important implications for the sustainability of rice farming in these countries. Second, the potential for increased productivity created by dramatic technological breakthroughs in the late 1960s has almost been exploited, particularly for irrigated and favorable rainfed environments. Nearly 40% of the rice land is subjected to droughts, floods, and poor drainage and has been bypassed by the Green Revolution. Unless rice scientists succeed in developing appropriate high-yielding varieties for these unfavorable environments, production growth will decelerate substantially in the near future.

Growing scarcity of agricultural inputs

The growing economic prosperity in Asia is a crucial factor that affects the availability of labor, water, and land for rice cultivation. Competing demand for these inputs from other economic activities affects their relative scarcities and prices, and changes the relative profitability depending on the intensity of their use in a particular activity.

Labor and wages. Economic growth brings dramatic changes in the structure of employment, adoption of labor-saving technology, and increases in labor productivity. With opportunities for more remunerative employment rising elsewhere, workers move out of low-productivity, low-wage food production activities. Although the agricultural sector tries to address the problem of labor shortage by adopting labor-saving technologies, it cannot compete with the manufacturing and services sectors, and so productivity differences continue to grow with economic prosperity. In South Korea, for example, labor productivity in manufacturing increased by 4.3 times during the 1966-90 period, compared with only 1.2 times in the agricultural sector. The total agricultural labor force increased from 4.5 to 6.1 million workers between 1966 and 1975, and then started declining in absolute terms and reached 3.2 million by 1990 (World Bank 1995).

Labor scarcity becomes reflected in the price of labor, the wage rate. In East and Southeast Asia, which experienced more than 5% per year growth in per capita incomes, the real wage rate increased by 170% over a 20-year period. In South Asia, where the economic growth was moderate, the real wage rate increased by only 50% (World Bank 1995). Table 1 shows the growth in nominal agricultural wage rates over the 1961 -91 period for selected Asian countries. In the early 1960s, the difference in wage rate across countries was only marginal. In the slow-growing countries, such as Bangladesh, India, and the Philippines, agricultural wage rates had hardly increased, but wage rates escalated in Japan and South Korea. The agricultural labor cost in 1991 was more than 20 times higher in Korea and 65 times higher in Japan than in Bangladesh.

Table 1. Relationship between economic prosperity and agricultural wage rate, selected Asian countries.

	Per capita income (US$)	Agricultural wage rate (US$ d^{-1})	
	1994	1966	1991
Bangladesh	220	0.63	1.39
Philippines	950	0.74	2.28
Thailand	2,410	0.48	2.51
South Korea	8,260	0.95	33.30
Japan	34,630	2.50	91.00

Source: IRRI 1995. World Rice Statistics 1993-94.

Availability of water. Water resource development has been the key to increasing rice production in virtually all Asian countries where land is a scarce production factor. Water has generally been regarded as an abundant resource for humid Asia. But with rapidly increasing population, the substitution of water for scarce land has taken place to meet growing food needs. As a result, the perception of water abundance has been changing in many Asian countries. The per capita availability of water resources declined by 40% to 60% in most Asian countries over the 1955-90 period (Fredericksen et al 1993). By common convention, countries are defined as water-stressed when the availability of water is between 1000 and 1700 m^3 per capita. Projections based on constant availability of water and increasing population suggest that China, India, Sri Lanka, Pakistan, and South Korea are expected to reach near stress levels by 2025.

As population increases and economic development intensifies, satisfying the needs for drinking water, sanitation, and industrial activities has to be accorded higher priority in allocating water resources. Economically prosperous Asia is now confronted with emerging water resource problems which include (a) the stress of meeting human and industrial needs in exploding urban centers, (b) plateauing of full economic exploitation of irrigation potential in many regions, (c) expansion of coastal salinity because of reduced river flows during the dry season, and (d) rising costs of flood and cyclone damage as economic activity expands into flood-prone and coastal areas. Almost all Asian governments now face difficult decision-making involved in long-term plans for regulation, allocation, and use of water resources.

The scope of further conversion of rainfed to irrigated land, which was the major source of past production growth, is also becoming limited (Rosegrant and Svendsen 1993). Irrigation cost has increased substantially, as easy options for irrigation development have already been exploited. Also, environmental concerns regarding the adverse effects of irrigation and flood control projects on waterlogging, salinity, fish production, and the quality of groundwater have been growing. Already, there has been a drastic decline in investment for the development and maintenance of large-scale irrigation projects in many Asian countries.

Competing demand for land. Economic prosperity and industrial progress are leading to rapid urbanization and concentration of people in a few large cities. Most of the additional increase in population beyond 2000 will be located in urban areas. By 2025, 53% of the people in Asia will live in urban areas compared with 30% in 1990 (UN 1995). An important implication of growing urbanization is that some of the fertile agricultural land has to be diverted to meet the demand for housing, factories, and roads. Also with urbanization and the associated change in food habits, markets for vegetables, fruits, and livestock products will grow stronger. Economic pressure will reduce the area under rice cultivation to accommodate those relatively high-value crops. Rice land has already started declining even in low- and middle-income countries such as China, Philippines, Indonesia (Java), and Bangladesh.

Future growth in rice production must occur on less land with less labor and less water. The downward pressure of input availability on the growth of supply is thus obvious.

Economic prosperity and competitiveness of *rice farming.* Despite the impressive increase in land productivity, it has been difficult for the fast-growing Asian countries to sustain producers' interest in rice farming. Because traditional rice farming is a highly labor-intensive activity, the growing labor scarcity and higher wages pushed up the rice production cost and reduced profits and farmers' incomes. It is not only wage laborers who are tempted to move to nonfarm urban and rural occupations; even small-scale rice farmers find it more attractive to leave rice farming and join the nonfarm labor force.

Competitiveness of rice farming is sought to be maintained through (a) improved farm management practices that increase efficiency in the use of nonland inputs and increase total factor productivity, (b) increased use of capital to replace labor through mechanization of farming operations so that labor productivity can be continually raised when no further increase in land productivity is possible, and (c) using the price mechanism to transfer income from the relatively well-off rice consumers to low-income rice producers so that the balance between rural and urban incomes can be maintained.

In spite of these policies, sustaining farmers' interest in rice cultivation has remained a major challenge to the fast-growing Asian countries. In regions where yield is high, such as in Japan and South Korea, the scope of increasing profitability through efficient use of inputs has almost been exhausted. Because labor accounts for only a fourth of the rice production cost, the substitution of capital for labor when the average farm size remains small increased farmers' income only up to a point. Land prices remained high and increased over time due to extreme population growth pressure and growing land demand for housing and industry. In South Korea, rural wage rates and land prices increased by 18% per year during the 1970-90

Table 2. Costs of production and farm-gate prices of paddy rice in selected countries, 1987-89.

Country	Cost of production (US$ t^{-1})	Farm-gate price (US$ t^{-1})	Paddy yield (t ha^{-1})	Share of labor in total cost (%)
Japan	1,987	1,730	6.5	28
South Korea	939	957	6.6	17
United States	195	167	6.3	5
Vietnam	100	130	4.6	17
Thailand	120	141	1.8	35
Bangladesh	138	180	2.7	32

Sources: FAO (1992) Economic and Social Development Paper 101. IRRI(l995) World Rice Statistics 1993-94.

period, when machinery and fertilizer prices increased by 7% (Park 1996).

As rice cultivation cost continued to increase due to the rising opportunity cost of labor and land, governments had to continually raise rice prices and increase farm subsidies to maintain the balance between rural and urban household incomes. Protection of the domestic rice industry encourages high-cost local production. In the late 1980s, the cost of producing rice in Japan was about 17 times higher than in Thailand and Vietnam and about 10 times higher than in the USA (Table 2). Thus, the comparative advantage in rice production has shifted to the low-income countries.

The implementation of the Uruguay Round of the GATT may further dampen incentives for rice production, particularly in middle- and high-income countries (Pingali et a1 1997). These countries will not be able to compete with low-income economies where the wage rate and the opportunity cost of family labor is low, or with large land-surplus countries in the developed world (e.g., Australia, USA) which reap economies of scale because of the large rice farms. If the domestic market is opened for competition, rice price will decline substantially, providing consumers with incentives to go for imported food staples and forcing farmers to abandon rice cultivation in favor of more lucrative economic activities.

An important way of gaining competitive strength in the face of rice trade liberalization is consolidation of tiny holdings into large-scale farms, as rural households migrate to urban areas, leaving their land behind. Farming in large-scale holdings in the developed world and the vertical integration of the rice industry (production, processing, and marketing managed by the same farm) may contribute to a more efficient use of large-scale machinery and reduce the number of part-time farmers involved in the supervision of numerous tiny farms. The main constraint to consolidation of holdings in Asia, however, is exorbitant land prices that prevent the development of an active land market. At existing land prices, the rate of return in rice farming from investment in land will be substantially lower than the return from investment in other enterprises.

Because of forces mentioned earlier, middle- and high-income countries will not be able to generate exportable surplus even when domestic rice consumption declines with growing economic prosperity. Rather, rice area and production will decline as domestic production is adjusted with a downward trend in demand.

Technological progress for sustaining production growth

The experience of the last three decades with the Green Revolution in rice cultivation generated a sense of complacency regarding Asia's ability to meet the growing demand for rice. Recent production trends raise serious concerns about rice sustainability. During 1985-95, rice production growth was only 1.7% per year, compared with 3.2% during 1975-85 and 2.9% one decade earlier. Rice production increases are failing to outpace population growth in several countries in Asia (Table 3).

The most important factor that contributed to the impressive growth of rice production in the past was the technological progress in rice cultivation. Scientists developed modem varieties that produce two to three times more yield than traditional varieties on lands with reliable irrigation. The increase in rice yield in the past originated mostly from (1) gradual adoption of modem varieties on existing irrigated land, and (2) expansion of irrigated land through public and private sector investment in water resource development.

The crucial reason behind the decline in rice production growth in recent years is that most farmers have already planted modem varieties in available irrigated land, and the best farmers'

Table 3. Recent trends in population and rice production, major rice-growing countries in Asia.

Country or area	Rice harvested area, 1995 (million ha)	Population growth (% year^{1}) 1975-85	Population growth (% year^{1}) 1985-95	Rice production growth (% year^{1}) 1975-85	Rice production growth (% year^{1}) 1985-95
China	31.1	1.4	1.4	3.2	0.7
India	42.3	2.2	2.0	2.4	3.1
Indonesia	11.5	2.1	1.7	5.5	2.5
Bangladesh	10.0	2.6	2.0	2.3	1.8
Vietnam	6.8	2.2	2.2	3.6	5.2
Thailand	9.0	2.1	1.4	3.0	0.5
Myanmar	6.2	2.1	2.2	4.6	3.1
Japan	2.1	0.8	0.4	-1.0	-1.1
Philippines	3.8	2.4	2.1	3.5	1.7
South Korea	1.1	1.5	1.0	1.8	-2.2
Asia	132.8	1.9	1.8	3.2	1.7
World	149.1	1.7	1.8	3.1	1.7

yields are already approaching the potential that scientists attained in their experimental fields with up-to-date knowledge. Because of intensive monoculture of rice on irrigated land and heavy use of chemical fertilizers and pesticides, soil and water quality has been deteriorating, and farmers find it difficult to sustain the high yield (Flinn and De Datta 1984, Cassman and Pingali 1995). In Japan and South Korea, rice yield remained stagnant at around 6.5 t ha^{-1} in the late '60s and late '70, respectively. In the humid tropics of South and Southeast Asia, maximum achievable yield is lower than in East Asia by at least 1 t ha^{-1} because of increased pest pressure and frequent cloudy days with below-optimal sunshine. In regions with good irrigation infrastructure, the maximum attainable yield is about to be reached.

The greatest potential for increasing rice production, however, lies in rainfed land, which accounts for almost half of total rice area. The yield in rainfed land had increased only marginally from 1.5 t ha^{-1} before the Green Revolution to about 2.0 t ha^{-1} in the early '90s (Hossain 1996). The rainfed ecosystem is subject to erratic natural factors such as floods, droughts, and typhoons, temporary submergence from heavy rainfalls, and tides and salinity in coastal areas. The risk in rice cultivation due to unreliable monsoons discourages poor farmers from adopting modem varieties and from investing in chemical fertilizers. Increasing yield in the rainfed system will, however, be difficult because scientists have had limited success in developing modem varieties that can withstand the climatic and soil-related stresses in the ecosystem. With recent advances in molecular biology, research on these issues has been accelerated, but the outcome is uncertain.

Supply response to prices

If rice supply lags behind increased demand, the price will increase. The resultant increase in marginal-value products may encourage farmers to use inputs in larger amounts that will raise the yield and reduce demand-supply imbalances.

Recent studies on dynamic supply response, however, suggest that the production response to prices for rice is typically small. A 10% increase in price would increase rice yield from 0.4% to 1.8%. The response comes mainly from fertilizer use and irrigation expansion, which would increase from 2% to 4% in response to a 10% increase in rice prices (Hossain 1997). But the output elasticity of fertilizer is small because land, water, and labor are still dominant inputs in rice production. In most Asian countries, chemical fertilizers were popularized among farmers with large amounts of subsidies. In recent years, however, Asian governments have started withdrawing subsidies from this input, which puts an upward pressure on farm-level prices. This price trend may reduce fertilizer use and rice yield in the irrigated ecosystem, which can only be compensated by an increase in technical efficiency in nutrient use. Also, with the declining availability of land and labor, the positive response from fertilizer efficiency will be offset by the negative response to reduced labor use.

Thus, although demand growth is expected to decline in the future, production growth may decelerate even further. So the demand-supply balance in the world rice market is expected to become tight, and we might see a reversal of the declining long-term trend of real rice prices (adjusted for inflation).

Sustaining food security through trade

So far, most Asian countries have followed a strategy of sustaining food security through self-sufficiency in the domestic production of staple grains. But a country does not necessarily require self-sufficiency in domestic production to achieve or sustain food security. Singapore and Hong Kong produce very little food grain but have better records of food security than major rice-growing countries in the region. Malaysia meets almost 40% of its rice needs through imports. What is important for food security is achieving self-reliance in food. It requires a favorable export growth at the national level that permits deficit countries to import food from surplus countries that can produce it at a lower cost, and at the household level generate productive employment that provides adequate income to acquire the needed rice from the market. Most countries in East and Southeast Asia are fortunate in this aspect. With growing economic prosperity and alleviation of poverty, they are able to fulfill this condition. In fact, as the cost of rice production increases with growing wage rates, land prices, and scarcity of water, it makes sense, if improving economic efficiency is the primary consideration, to readjust resources away from labor-intensive rice cultivation.

We must, however, take a dynamic view of the issue. What will happen if every country in Asia abandons production of staple grains to release resources for more profitable economic activities, and opts for sustaining food security through international trade? No doubt, many Asian countries will have the economic capacity to import rice, and affluent Asians may be willing to pay much higher prices for their preferred food staple. In Japan and South Korea, consumers now pay for domestic rice 10-15 times more than the price at which they could procure it from the world market. In the future, who will produce the exportable surplus for them? In view of the growing shortage of land and water, will rice supply increase substantially in response to higher prices? What would be the political response in rice-exporting countries to international transactions in staple food when trade generates scarcity in the domestic market? What would be the impact of rising food prices on inflation and other macroeconomic variables? The answers to these questions have important implications for the strategy for sustaining food security through trade for the affluent Asian nations.

An important element of uncertainty in depending on international trade for ensuring adequate rice supply is the thinness of the world market. Only 4% of the rice is traded in the world market compared with 20% for wheat and 11% for coarse grains. Variable natural conditions such as floods, droughts, and typhoons cause shortages and surpluses to occur from year to year, which produce wide fluctuations in marketable surplus and import needs, and make the world rice market highly volatile.

Another factor to consider is the influence of the giant economies of Asia-China, India, and Indonesia—on the world rice market. The size of the international rice market is equivalent to only 13% of the rice needs in China, and 8% of the combined consumption of India and China. If these countries decide to meet only 10% of their rice needs through imports, the additional demand could swamp the world market. The volatility of the world market for rice is demonstrated by the surge in prices of quality rice during October 1993 to April 1994 in response to a 25% reduction in production in Japan due to abnormal weather.

Given the adequate increase in rice prices, there is some potential for the expansion of rice area in the humid tropics of Africa and Latin America (FAO 1993). It is estimated that there are 20 million ha of potentially suitable rice land in river valleys in West and southern Africa, of which only 15% are currently cultivated. In tropical South America, rice cultivation could be extended to an additional 20 million ha. Exploitation of this potential, however, will require a substantial increase in prices, as well as the capacity of countries to invest in the reclamation of land and the development of marketing infrastructure.

The unit cost of production and the marketing margin are many times higher in Africa and Latin America than in Asia (Ahmed and Rustagi 1987). Also, the demand for rice has been growing faster in other continents than in Asia. So the exportable surplus available for Asia from other continents could be quite small.

In Asia, eastern India has considerable excess rice production. With alleviation of poverty and high population growth, eastern India may need to exploit the excess capacity to meet its growing internal demand. Only Thailand, Myanmar, and Cambodia could generate additional exportable surplus to partially meet potential shortages in other Asian countries. Exploitation of the potential, however, would require substantial investment in land reclamation, expansion of irrigation, technologies for improving rice quality, and development of marketing infrastructure. Myanmar and Cambodia do not have the economic capacity to make such investments and may not be able to mobilize international support due to their political situations.

Given free trade in rice, it is not difficult for high-income food-deficit countries and affluent consumers to obtain rice from the market, even when there is a scarcity. The market will distribute the scarce supplies in favor of the affluent who can pay higher prices. It is the poor consumers in the low-income countries who will suffer when there is a scarcity in staple food. When prices soar, the government may intervene in the market to protect the interests of the low-income rural and urban poor. Imposing a ban on exports of staple food when there is a scarcity in the domestic market is not a rare phenomenon. Food scarcities are often used by stronger nations as an important weapon to interfere in the domestic politics of weaker nations (Iraq and North Korea are recent examples). Considering the political cost, many Asian countries may find it in the national interest to maintain a safe capacity of domestic staple food production despite the additional economic cost of pursuing this policy.

Demand-supply balance for China

China has earned recognition for its ability to feed over one-fifth of the global population with only one-fifteenth of the arable land. China has had a consistent surplus in food trade since 1984, although its grain import has been increasing. Even in 1995, when China’s net grain import hit a high of 18.7 million t (1 1.6 million t of wheat and 5.2 million t of maize), there was still a surplus in food trade of US3.82 billion due to substantial export of nongrain food such as meat, poultry, and eggs (Bingsheng 1997). Will China sustain this trend into the 21 st century?

With a continued increase in population, rising incomes and aspirations, and depletion and degradation of natural resources, China’s capacity to sustain food security through domestic production has recently come under the spotlight. The concern has been fueled by the stagnancy of the Chinese grain production sector since 1990. Lester Brown’s (1995) gloomy projection of the Chinese food situation into the early 21 st century and its potential disastrous effect on the world grain market and food security in low-income countries has generated heated discussions in many circles in and outside China and has stirred the thinking of Chinese policymakers.

Few would disagree with the proposition that China is going to experience substantial deceleration in the demand for grain as food over the next two decades. The per capita consumption of food grain has started declining in China after reaching its peak in 1984, although only marginally. This downward trend will accelerate as the Chinese economy continues to prosper. The current level of per capita food grain consumption is 20% higher in China than in South Korea and 54% higher than in Japan (Table 4). Total food grain consumption is not expected to increase much further because the upward pressure in demand due to population growth will be partly offset by the decline in per capita consumption in grains. IFPRI 2020 projections (Huang, Rosegrant, and Rozelle 1995) show that rice demand will probably increase at a rate of only 0.5% per year over the 2000-2020 period.

In China, per capita consumption of meat and fish has been increasing by a staggering 9% per year since the early 1980s, but the present consumption level is still about 53% lower than in Japan and 45% lower than in South Korea (Table 4). The potential for increasing the supply of aquatic products is much more limited in China than in Japan and South Korea because of large inland areas. So the pressure will be on increasing the supply of poultry and livestock products. Therefore, China will need to produce large amounts of feed grains to meet this expected fast-growing demand for meat and eggs. In China, the use of feed grains per capita is only 36% of that in Japan and 24% of that in the USA. As China approaches the consumption standards of developed countries with its fast economic progress, its demand for feed grains will grow rapidly. If maize is diverted from food to feed grains, rice consumption in maize-consuming provinces might increase. The use of low-quality rice as feed grain might also increase. So, production of rice will have to grow at a faster rate than the increase in demand for rice as food.

The decline in per capita rice consumption at higher income levels will take place precisely because of the tendency of consumers to acquire more energy and proteins from vegetables, fruits, fish, and livestock products. Per capita consumption of vegetables in China is one-third lower than that in South Korea. The situation is similar in fruits (Table 4). China will thus have to allocate more land for fruit and vegetable production, which will probably come largely from reduced rice production in well-drained uplands, particularly in peri-urban areas, and reduced area under early-season rice in double-cropped rice-growing areas, because such land is also suitable for growing vegetables. The area under vegetables increased by 5.5% per year during the 1978-90 period, and further accelerated to 8.5% per year during 1990-95. The area under orchards increased by 9.4% during this period (Table 5). It seems that the substantial decline in area under rice and wheat in the 1990s is largely due to the release of land for vegetables and orchards. This trend is expected to continue in the future. Even if the area under orchards and vegetables grows at a lower rate of 3% per year over the next 25 years, and two-thirds of the land is obtained from releasing area now allocated to rice and wheat, cropped area under rice and wheat will shrink by 1 % per year. Thus, to achieve a production growth of 0.5% per year with reduced land resources, the target for yield growth for rice and wheat has to be fixed at 1.5% per year.

Table 4. Per capita consumption (g d^{-1}) of food in China compared with selected countries, average 1992-94.

Country	Cereals			Vegetables and roots	Fish and seafood	Meat and eggs	Fruits
	As food	As live-stock feed	Total				
China	614	146	760	396	47	121	78
South Korea	513	388	901	554	181	125	229
Japan	400	408	808	391	188	170	161
Indonesia	561	54	615	246	43	32	90
USA	315	610	925	463	60	370	412

Source: FAO (1996) Food Balance Sheets, 1992-94 average, Rome.

Table 5. Trends in area sown to different crops in China, 1978 to 1995.

Crop	Sown area (million ha)			Annual growth rate (%)	
	1978	1990	1995	1978-90	1990-95
Rice	34.4	33.1	30.7	-0.3	-1.5
Wheat	29.2	30.8	28.9	0.5	-1.2
Maize	20.9	21.4	22.8	0.6	1.2
Vegetables	3.3	6.3	9.5	5.5	8.5
Orchards	1.7	5.2	8.1	9.9	9.4

Source: China Statistical Yearbook 1996.

Although Chinese consumers may reduce their rice consumption as their incomes increase, they might be willing to spend more for the quality of their choice. South Korea achieved self-sufficiency in rice production in the 1970s through the adoption of Tongil, a high-yielding indica variety. But consumers later shifted to japonica rice as their incomes continued to grow. The shift from standard to quality rice has also taken place in Japan as the economy continued to develop (Fig. 1). From the experience of Japan and South Korea, we can predict that the demand for japonica and high-quality indica rice will continue to grow very fast in China over the next two decades, although total demand may grow slowly. Already the gap in the price of japonica and indica rice has started growing, which is an indication of the scarcity of japonica rice in the market. So increasing the supply of high-quality rice should figure prominently in the future rice production strategy in China.

Will China be able to sustain a growth rate in rice yield of 1.5% to 2% per year? The challenge may not appear daunting in view of the 3% plus annual growth in grain yield achieved over the past four decades. The pessimism, however, comes from the recent drastic deceleration in yield rate growth (Table 6). For rice, growth rate has declined from 3% per year during the 1978-90 period to only 1% during 1990-95. For wheat, growth has decelerated from 4.7% to 2% over these periods.

But we should recognize that because of its vast land mass and diverse agroecological situation, China can grow almost any agricultural produce as efficiently as anywhere else in the world. Although China has achieved high yield levels, it has moderate to large yield gaps in grain production compared with standards achieved by some countries. The most favorable environment for grain production probably prevails in Egypt where crop yield achieved by farmers is one of the highest in the world. If China could reach that level, yield would increase by 27% for rice, 34% for maize, and 50% for wheat. There is also a large yield gap among various provinces in China (Fig. 3). By 1995 rice yield reached 8.0 t ha^{-1} in Jiangsu compared with 5.0 t in Jianxi and Fujian. Wheat yield reached 5.9 t ha^{-1} in Anhui and 5.2 t ha^{-1} in Shandong compared with only 4.1 t ha^{-1} in Hainan. If these interprovincial yield gaps could be eliminated by 2020, rice yield would grow by 1.2% per year and wheat yield by 2%.

Table 6. Sources of growth (%) in cereal grain production, 1978 to 1995.

Crop	Period	Crop area	Yield rate	Production
Rice	1978-90	-0.3	3.0	2.7
	1990-95	-1.5	1.0	-0.5
Wheat	1978-90	0.5	4.7	5.2
	1990-95	-1.2	2.0	0.8
Maize	1978-90	0.6	4.1	4.7
	1990-95	1.2	1.7	2.9

Source: Own estimates from China Statistical Yearbook 1996.

But reducing the yield gap may not just be a matter of time. Growth sources in rice production in China over 1978-92 indicate that research for technology development has been the most important factor that compensated for the negative effects of forces such as the reduction in availability of land and labor and increase in fertilizer prices (Table 7). Thus, the government must continue to provide strong support for research and extension for development and transfer of technologies to farmers. We also believe that, with further marketing reforms to achieve greater efficiency in the interprovincial distribution of food, provision of proper economic incentives to farmers, further expansion and efficient use of irrigation infrastructure, and extension of improved crop management practices, China will fully exploit the comparative advantage of different regions in the production of various grains and may eventually eliminate these yield gaps.

Conclusions

Recent projections on China's food grain supply-demand balances indicate that, if the "business-as-usual" scenario prevails, China's import dependence might increase from 5% of domestic consumption at present to nearly 10% by 2020. Some Chinese scholars also argue that the opening up of the domestic market of grains for free trade and gradual adoption of the self-reliance policy instead of self-sufficiency for sustaining food security may also be desirable

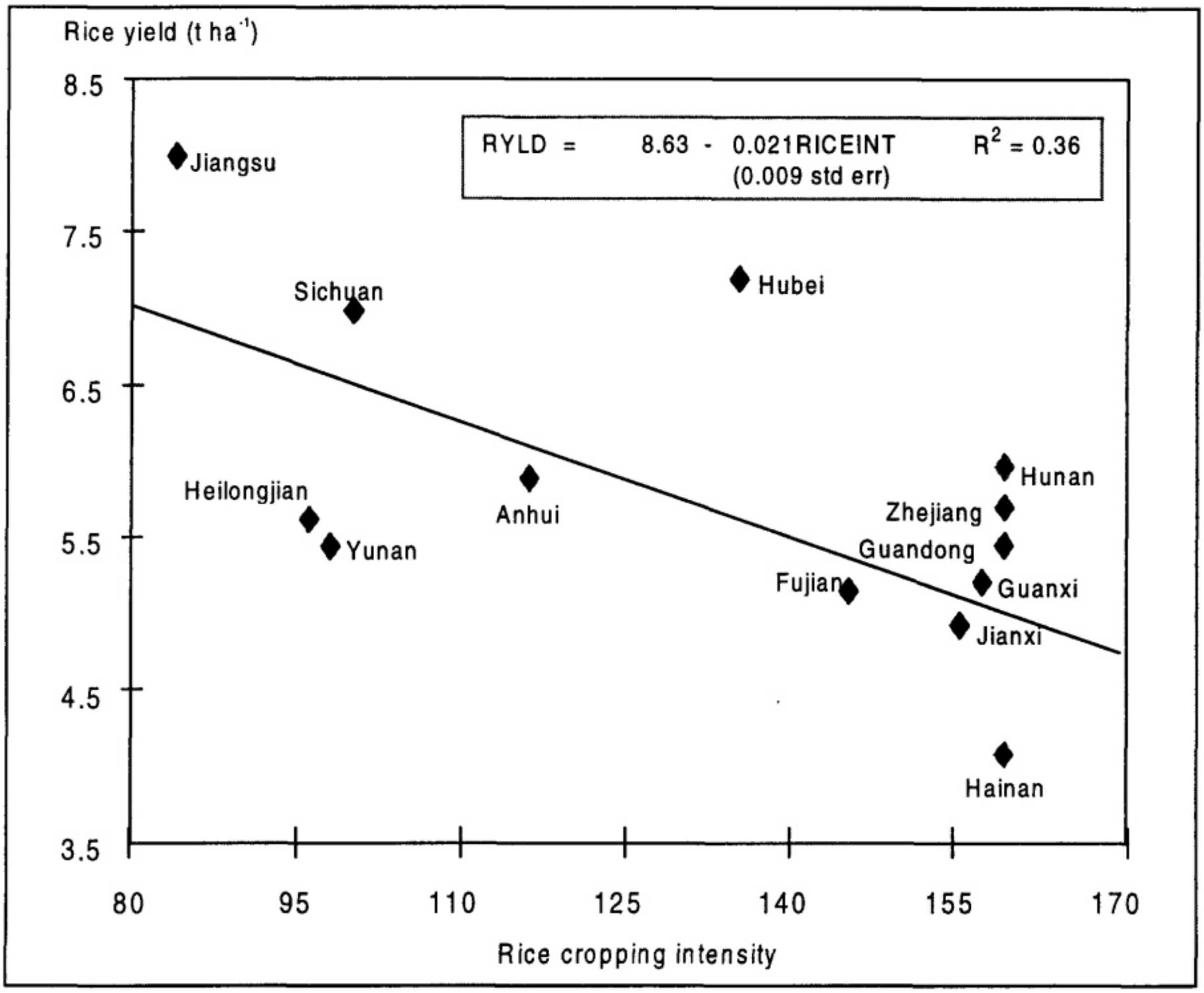


Fig. 3. Relationship between cropping intensity and yield of rice in major rice-growing provinces, China, 1995. Source: China statistical yearbook 1996.

for economic efficiency and keeping the trade partners happy.

China will have no financial problem in importing 10% or more of its food grain consumption because of the fast growth in incomes and export earnings. But it is debatable whether it is in China's national interest to opt for a policy of self-reliance and greater dependence on the international market for staple grains. The dominant considerations in the debate would be political economy factors such as (a) exposure to the use of international trade by powerful food-exporting countries for influencing domestic policies of food-deficit countries, (b) pursuing the policy of self-sufficiency in staple grains by most countries in the world market, (c) China's own need to protect the domestic market so it can use internal terms of trade as a policy tool to reduce income disparity between rural and urban areas and among provinces.

Table 7. Sources of rice production growth in China, 1978-92.

Factor	Rates of growth (% year^{1})	Contribution to growth (% of total)
Technology development	2.2	94
Public investment	0.1	5
Institutional innovation	0.7	29
Fertilizer price	-0.4	-16
Rice price	0.4	18
Land availability	-0.2	-6
Labor availability	-0.4	-16
Environmental factors	-0.1	-3
Residual	-0.1	-4
Total	2.4	100

Source: Huang, Rosegrant, and Rozelle (1995).

China's share of global grain production now stands at 34% for rice and 20% for wheat and maize. If China decides to procure 10% of its rice needs from the world market, the import demand will increase by 67%, which is expected to put substantial upward pressure on prices. In China, rural-urban and interprovincial disparity in income has been growing fast, and has become a matter of great concern to policymakers. In 1995, per capita income for urban areas was 120% higher than for rural areas; during the 1985-95 period, real income grew by 35% for rural households compared with 78% for urban households (China Statistical Yearbook 1996). Instead of paying higher prices to surplus grain producers in other countries, Chinese policymakers may find it in the national interest to manipulate the domestic terms of trade in favor of staple grains to provide incentives to farmers to reduce the yield gap and to raise their incomes in the slow-growing western and central provinces. Like Japan and South Korea, the Chinese government will need to keep its control over the domestic market and international trade in rice to effectively use this policy.

References

Ahmed R, Rustagi N. 1987. Marketing and price incentives in African and Asian countries: a comparison. In: Dieter ELZ, editor. Agricultural marketing strategy and pricing policy. Washington, D.C.: World Bank.

Bender W, Smith M. 1997. Population, food and nutrition. Pop. Bull. 51(4):5-7.

Bingsheng K. 1997. Policy and institutional change for agriculture in China: production, consumption and trade implications. Paper presented at the Congress for the International Association of Agricultural Economists, Sacramento, California, August.

Brown L. 1995. Who will feed China? Wake-up call for a small planet. New York: W.W. Norton and Co.

Cassman KG, Pingali PL. 1995. Extrapolating trends from long-term experiments to farmers' fields: the case of irrigated rice systems in Asia. In: Barnet V, Payne R, Steiner R, editors. Agricultural sustainability: economic, environmental and statistical considerations. New York: John Wiley and Sons Ltd.

Flinn JC, De Datta SK. 1984. Trends in irrigated rice yields under intensive cropping at Philippine research stations. Field Crops Res. 9:l-15.

Food and Agriculture Organization. 1993. Agriculture towards 2010. Rome: FAO.

Fredericksen HD, Berkoff J, Barber W. 1993. Water resource management in Asia. Vol. 1, Main Report. World Bank Technical Paper No. 212. Washington, D.C.: The World Bank.

Hossain M. 1996. Sustaining food security for rainfed ecosystems in Asia. Asia Pacific J. Rural Dev. 6(1): 1-22.

Hossain M. 1997. Rice supply and demand in Asia: a socioeconomic and biophysical analysis. In: Teng PS, editor. Applications of systems approaches at the farm and regional levels. Kluwer Academic Publishers.

Huang J, Rosegrant MW, Rozelle S. 1995. Public investment, technological change and agricultural growth in China. Paper presented at the Final Workshop of IRRI-IFPRI Project on Projections and Policy Implications of Medium and Long-term Rice Supply and Demand, 23-26 April, Beijing, China.

Huang J, Rozelle S, Rosegrant MW. 1995. Supply, demand and China's future grain deficit. Paper presented at the Final Workshop of IRRI-IFPRI Project on Projections and Policy Implications of Medium and Long-term Rice Supply and Demand, 23-26 April, Beijing, China.

Park JK. 1996. Economic modernization and impact on agricultural output and input markets in Korea. In: Pingali PL, Paris TR, editors. Proceedings of the Workshop on Social Science Methods in Agricultural Systems: Coping with Increasing Resource Competition in Asia, Chiang Mai. IRRI Discussion Paper Series No. 11. Los Baños, Philippines: IRRI.

Pingali PL, Hossain M, Gerpacio RV. 1997. Asian rice bowls: the returning crisis? Wallingford, UK: CAB International.

Rosegrant MW, Agcaoili-Sombilla M, Perez N. 1995. Global food projections to 2020: implications for investment. Food, Agriculture and the Environment Discussion Paper No. 5. Washington, D.C.: International Food Policy Research Institute.

Rosegrant MW, Svendsen M. 1993. Irrigation investment and management policy for Asian food production growth in the 1990s. Food Policy 18: 13-32.

State Statistical Bureau, People's Republic of China. 1996. China statistical yearbook 1996. Beijing: China Statistical Publishing House.

United Nations. 1995. World urbanization prospects. New York: UN.

World Bank. 1992. World development report, 1990. Oxford University Press.

World Bank. 1995. World development report, 1995. Oxford University Press.

Concluding remarks

Ren Wang
Vice President, CAAS

Dr. Rothschild, Colleagues, Ladies, and Gentlemen:

The 2-day "China-IRRI Dialogue" has come to an end. It has been a privilege for the Chinese Academy of Agricultural Sciences to be the host of this important event. And as a coorganizer with IRRI, we are very pleased to see that the Dialogue has achieved its primary objectives.

First of all, the organizers and the participants enjoyed the session on reviewing the past achievements of the IRRI-China cooperation. We heard citations of joint research concerning various aspects of rice production, the number of Chinese trainees who have benefited from their research and participation in workshops at IRRI, and the new varieties and techniques used in China's rice fields as a result of our cooperative research. It is really stimulating as well as satisfying to learn that these new varieties and techniques have been used in such large areas in China. The joint efforts of IRRI and Chinese scientists and farmers have made significant contributions to China's rice production in the past 20 or more years. I am very glad that IRRI and our joint achievements are recognized by the Chinese government, our scientific community, and Chinese rice farmers.

Second, we have seen a healthy expansion in collaboration between IRRI and Chinese agricultural research organizations. The representation of a wide range of Chinese universities and organizations at various levels reflects this. The organizers appreciate the enthusiastic participation and important contribution of the Chinese Academy of Sciences, China Agricultural University, Wuhan University, Wuhan University of Hydrology and Electricity, as well as other key agricultural universities and, particularly, the agricultural academies of 16 provinces, which are all major rice producers. I would like to emphasize again that CAAS would like to strengthen our ties in rice research not only with IRRI but also with our Chinese universities and research organizations. It would be gratifying if CAAS could play a meaningful role, under the leadership of our Ministry of Agriculture, in coordinating IRRI-China cooperation, in facilitating interaction and collaboration between IRRI and Chinese institutions, and in working together in IRRI-China research activities. This is why we think that it is most rewarding to see the success of this dialogue.

Third, we have identified 12 subjects for cooperative work and have developed frameworks or drafts of proposals for these initiatives. I have noted that these project initiatives and workplans cover both applied work and fundamental research, which is very much in line with the current priority and emphasis of the Chinese government on agricultural development in general and rice research in particular.

Ladies and gentlemen, this dialogue is held at a particularly good time. Dr. Song Jim, Chairman of the State Science and Technology Commission (SSTC), emphasized during his meeting with Dr. Rothschild at the State Council that the Chinese government is determined to strengthen our agricultural research and to gradually make agriculture the priority across all disciplines of science and technology development. Last September, President Jiang

Zemin called for a “new revolution in agricultural science and technology” in China to ensure an adequate food supply for the Chinese people and economic development. Recently, CAAS has been actively involved in the development of a new “Climbing Program” of the SSTC, capitalizing on fundamental research, and a number of major initiatives in materializing the “new revolution.” Dr. Song has invited IRRI to collaborate with Chinese institutions in such basic research, and we are keen to follow up on his suggestion.

At this point, I would like to make some suggestions on how to follow up on the outcomes and initiatives of our dialogue. Our actions may well include formation of “mega” projects involving IRRI and a number of Chinese institutes and/or provinces to address some key issues in a general framework. For instance, how about forming a multidisciplinary research project and calling it the “Chinese iron rice bowl program?’ Such a program may include initiatives on breeding, cropping systems, irrigation, nutrient and pest management, etc. We could submit it to the Chinese government as well as to external sources for funding. The Chinese funding may be used to support Chinese institutes while the external funding could be used to cover the costs of IRRI’s participation. This is just a thought for deliberation. At the moment, there is a possibility that the World Bank will provide China with a loan grant to support agricultural research. This grant may be used to establish or strengthen the existing competitive grants system for agricultural research in China. Our project proposals would fit into the categories of such competitive grants.

The development of such joint proposals could be carried out by our provincial academies and/or universities alone or together, or with CAAS. In any case, CAAS would be happy to serve a coordinating and facilitating role to help develop and submit the proposals. Mr. Gong Xi-feng, Division Chief of the International Cooperation Department of CAAS, will be your focal contact point.

Ladies and gentlemen, we are aware and have heard repeatedly during this meeting that China is one of the world’s largest countries in both rice production and consumption. Rice accounts for 43.6% of our total grain production. We are also aware of the limitations to and challenges for increasing our rice production. These include the increasing demand in both quantitative and qualitative terms by our still increasing population, the declining area of arable land, the deterioration of natural resources, and the uneven economic development of the coastal regions and central and western provinces. We have set our focus on intensifying technological inputs in production and our strategy of pursuing sustainable development. The direct technical objective would be to increase unit yield while conserving natural resources and the environment, which we believe is a key issue for research at present, and to ensure our food supply for the 21st century. Our aim is to achieve a total annual rice production of 200 million t by 2000 and 218 million t by 2010. We know that this is a steep hill to climb, but we are confident of achieving the goal, especially with the help of IRRI.

Dear colleagues, our job does not end after today’s meeting. Meetings are beginnings. What we should do after this 2-day meeting is to follow up on initiatives and existing projects, implement our plans, and pursue proposals to turn our dreams into reality.

More than 10 Chinese institutions now participate in IRRI-China joint research programs. While complimenting past achievements and expecting expansion of the cooperation, we have also felt the difficulties and sometimes confusion and frustration in managing and coordinating the projects with an increasing number of participating institutions. IRRI has now decided to establish a liaison office in Beijing, at CAAS, as a proactive strategy and approach to address this very issue. It demonstrates the sincerity and confidence of IRRI, as well as CAAS, in maximizing the potential of our cooperation. We have no doubt that the liaison office will serve well its bridging role in facilitating IRRI projects in China and strengthening IRRI’s relations with the Chinese government and the research community. We have observed in the past 10 plus years the successes and satisfying experience of the liaison offices of the International Potato Center and the International Plant Genetic Resources Institute, both located at CAAS.

Once again, ladies and gentlemen, let me thank you, on behalf of CAAS, for your participation and contribution to this highly successful workshop. Let us commit ourselves to working hand in hand by marching into the bright 21st century.

Thank you.

ANNEX 1
Participants in the IRRI-China Dialogue

CHINA

Chen Jiakuan
Wuhan University
Wuhan, Hubei
Tel: 027-788271 2
Fax: 027-882661

Chen Jianping
Zhejiang AAS
198 Shiqiao Rd.
Tel: 0571 -6400700-2005
Fax: 0571 -6400481

Chen Wenfu
Shenyang Agricultural University
Shenyang
Tel: 024-8421 266
Fax: 024-841 741 6

Chen Yiyi
Deputy Director
Crop Research Institute
Hubei AAS
Wuhan, Hubei
Tel: 027-7389584
Fax: 027-7389604

Cheng Jiaan
Zhejiang Agricultural University
Hangzhou, Zhejiang
Tel: 0571 -39711 07
Fax: 0571 -6041 052

Fang Zhiyong
Henan AAS
Zhengzhou
Tel: 0371 -571 7952
Fax: 0371 -571 5095

Ge Song
Plant Research Institute, CAS
Beijing
Tel: 62591 431 -6378
Fax: 62590843

Guo Yixian
Crop Research Institute
CAAS
Beijing 100081
Tel: 621 76667-2056
Fax: 621 741 42

He Guangcun
Living Science College
Wuhan University
Wuhan, Hubei
Tel: 027-788271 2-2384
Fax: 027-7882661

He Qingrui
Crop Research Institute, Yunnan AAS
Kunming, Yunnan
Tel: 0871 -521 2202
Fax: 0871 -5212202

Hong Deyuan
Plant Research Institute, CAS
Beijing
Tel: 62591 431 -6096
Fax: 62590843

Huang Bingchao
Plant Protection Institute
Guangdong AAS
Guangzhou
Tel: 020-87597463
Fax: 020-87597453

Huang Jikun
Agricultural Economic Institute
No. 30 Baishiqiao Rd.
CAAS
Beijing 100081
Tel: 01 0-621 76604
Fax: 01 0-621 78579
E-mail: ccap@public3.bta.net.cn

Huang Zhongxiang
Rice Research Institute
Anhui AAS
40 Nongkedong Rd., Hefei, Anhui
Tel: 0551 -5522233-2446
Fax: 0551 -5538825

Huang Zonghong
Rice Research Institute
Guizhou AAS
Tel: 0851 -381 3727
Fax: 0851 -371 3504

Li Kexiang
Crop Research Institute
Hainan AAS, Hainan
Tel: 0898-5874484
Fax: 0898-5875304

Li Xiaofen
CAAS
Beijing 100081
Tel: 641 92436
Fax: 641 92448

Li Zhilin
South China Agricultural University
Guangzhou
Tel: 020-8551 1299-3509
Fax: 020-8551 0589

Li Zichao
China Agricultural University
Beijing 100094
Tel: 010-62892936
Fax: 01 0-62582332

Liang Qu
International Cooperation Department, CAAS
Beijing 100081
Tel: 01 0-621 851 81
Fax: 01 0-621 74060

Lin Cang
Fujian AAS 350003
Fuzhou, Fujian
Tel: 0591 -7841 771
Fax: 0591 -7840650

Liu Guodong
Institute of Agricultural Resources and Regional Planning, CAAS
Beijing 100081
Tel: 621 7861 2
Fax: 621 7861 2

Liu Jianhua
Plant Protection Institute, Hunan AAS
Changsha, Hunan
Tel: 0731 -4081 429
Fax: 0731 -4081 429

Lu Feijie
Chinese Academy of Agricultural Sciences
Beijing 100081
Tel: 621 86602
Fax: 621 741 42

Mao Zhi
Wuhan University of Hydraulic and Electric Engineering
Wuhan, Hubei
Tel: 027-782221 2-2468
Fax: 027-7884496

Min Shaokai
China National Rice Research Institute
Hangzhou, Zhejiang
Tel: 0571-3371711
Fax: 0571 -51 70550,3371 745

Pan Xigan
Jiangxi AAS
Nanchang, Jiangxi
Tel: 0791 -571 4433-2086
Fax: 0791 -571 71 85

Wang Guanghuo
Zhejiang Agricultural University
Huajiachi, Hangzhou
Tel: 0571 -39711 07
Fax: 0571 -604981 5

Wang Jingyu
Rice Research Institute
Jilin AAS
Gongzhuling, Jilin
Tel: 0434-6351505
Fax: 0434-6351403

Wang Lianfang
Hunan Rice Research Institute
Changsha, Hunan
Tel: 0731 -4961250
Fax: 0731 -4690051

Wang Ren
CAAS
Beijing 100081
Tel: 62185573
Fax: 62174142

Wang Xiangkun
China Agricultural University
Beijing 100094
Tel: 010-62892936
Fax: 010-62582332

Wu Shangzhon
Guangdong AAS
Guangzhou, Guangdong
Tel: 020-87596241
Fax: 020-87503358

Wu Xiaojin
Hybrid Rice Research Center
Hunan AAS
Changsha, Hunan
Tel: 0731 -4080755
Fax: 0731 -4691 877

Xie Huaan
Fujian AAS
Fuzhou
Tel: 0591-7841771
Fax: 0591-7840650

Yang Rencui
Fujian Agricultural University
Fuzhou, Fujian
Tel: 0591-3741844
Fax: 0591-3741251

Ye Zhihua
Dept. of Sciences and Technology, CAAS
Beijing 100081
Tel: 010-62174433-2708
Fax: 010-62172990

Ying Cunshan
China National Rice Research Institute
Hangzhou, Zhejiang
Tel: 0571-3371711
Fax: 0571-5170550,3371745

Yu Chuanyuan
Hybrid Rice Research Center
Nanchang, Jiangxi
Tel: 0791-5714433-2221
Fax: 0791-5716785

Yuan Longping
Hunan Hybrid Rice Research Center
Changsha, Hunan
Tel: 0731 -4080755
Fax: 0731 -4691 877

Zeng Delu
Key Program Division
Yunnan AAS
Kunming, Yunnan
Tel: 0871-3140939
Fax: 0871-3136444

Zhang Gaiping
Henan AAS
Zhengzhou, Henan
Tel: 0371-5717952
Fax: 0371-5715095

Zhong Li
Foreign Affairs Office
Yunnan AAS
Kunming, Yunnan
Tel: 0871-5150089
Fax: 0871-5150089

Zhou Kaida
Rice Research Institute
Sichuan Agricultural University
Wenjiang County, Sichuan
Tel: 028-2722918
Fax: 028-2726875

Zhou Yang
Henan AAS
Zhengzhou
Tel: 0371 -5717952
Fax: 0371 -571 5095

Zhu Yingguo
Genetic Research Institute of Living Science College
Wuhan University
Wuhan, Hubei
Tel: 027-788271 2-4560
Fax: 027-7882661

Zhu Zhihua
Crop Germplasm Research Institute, CAAS
Beijing 100081
Tel: 621 86649
Fax: 621 86629

Zou Jiangshi
Vice President
Jiangsu AAS
Xiaolingwei, Nanjing
Tel: 025-439001 8
Fax: 025-4432691

INTERNATIONAL RICE RESEARCH INSTITUTE

MCPO Box 31 27,1271 Makati City
Philippines
Tel: (63-2) 845-0563
Fax: (63-2) 891 -1 292

Vethaiya Balasubramanian
International Programs Management Office

Mark Andrew Bell
Central Research Farm

Glenn Denning
International Programs Management Office

Achim Dobermann
Soil and Water Sciences Division

Kong Luen Heong
Entomology and Plant Pathology Division

Mahabub Hossain
Social Sciences Division

Osamu Ito
Agronomy, Plant Physiology, and Agroecology Division

Gurdev Khush
Plant Breeding, Genetics, and Biochemistry Division

Julian Lapitan
International Programs Management Office

Hei Leung
Entomology and Plant Pathology Division

Baorong Lu
Genetic Resources Center

Twng Wah Mew
Entomology and Plant Pathology Division

Shaobing Peng
Agronomy, Plant Physiology, and Agroecology Division

George Rothschild
Director General

Shengxiang Tang
IRRI Liaison Office in Beijing
CAAS
Beijing 100081
Tel: +86-10-62172964
+86-10-62174433 ext. 2309
Fax:+86-10-62174060
Email: IPGRI-CAAS@cgiar.org

Paul Teng
Entomology and Plant Pathology Division

To Phuc Tuong
Soil and Water Sciences Division

Robert Zeigler
Entomology and Plant Pathology Division

ANNEX 2
Twelve priority research projects

A. Plant Breeding and Genetic Resources

1. Improvement of grain filling
2. *In situ* conservation study of wild rice in China: *Oryza granulata* and *O. officinalis*
3. Breeding new plant type: rice with super high yield
4. Screening and utilization of heterotic genes in different rice groups or ecotypes
5. Selection and utilization of new sources of bacterial leaf blight resistance in wild rice

B. Resource Management and Social Sciences

1. Designing efficient rice farms for 21st century China
2. Achieving economical and sustainable water-efficient irrigation in rice-based systems in China
3. Enhancing potassium efficiency in relation to N, Zn, and Si nutrition in high-yielding rice
4. Policies for reducing yield gaps and sustainable rice production

C. Pest Management

1. Relationship between pesticide use and insect problems under high-yielding production systems in China
2. Integration of host plant resistance (transgenes) and biological control for sustainable management of rice sheath blight
3. Germplasm diversification and gene deployment for disease control

A. Plant Breeding and Genetic Resources

1. Improvement of grain filling

Rationale

- Grain filling becomes a problem when sink size is increased to raise yield potential.
- Current hybrid rice has lower grain-filling % than conventional rice (80% vs. 90%).
- Grain filling is more problematic in intersubspecific hybrid rice.
- Grain quality is closely related to grain filling.
- Research on grain filling has received great attention in China and at IRRI.

Objectives

- Identify the causes of poor grain filling in hybrid and new plant type rice
- Develop physiological and biochemical selection criteria for breeding program
- Improve the grain filling of hybrid rice from 80% to 90%

Expected outputs

- Knowledge on grain filling generated and 5 papers published
- Grain filling of hybrid rice improved
- Breeding strategies and selection criteria established

Activities

- Study root activities in relation to leaf senescence and grain filling
- Determine the anatomy and function of conductive tissue in assimilate remobilization
- Investigate the effects of enzymatic

activities and cell division of endosperm and hormonal content on sink strength
- Determine the proportion of indica and japonica background on grain filling
- Compare the effect of WC genes and backcrosses on the improvement of grain filling
- Establish the relationship between C and N accumulation rate of grains and grain quality

Milestones
- Publications
- Grain-filling percentage of hybrid rice

Partners
- Shenyang Agricultural University
- Yangzhou Agricultural University
- CNRRI
- Sichuan Agricultural University
- China Agricultural University
- APPA and PBGB Divisions, IRRI

Resources
- US$ 100,000 per year for 4 years

2. In situ conservation study of wild rice in China: *Oryza granulata* and *O. officinalis*

Rationale
- Wild rice species are important genetic resources for rice breeding, e.g., *O. granulata* (upland species) and *O. officinalis:* resistant to diseases and insect pests.
- Their distribution in the north region limits the targeted species.
- Endangered status; protection of the species is urgently needed.

Objectives
- Conduct ecogeographic survey of targeted species in targeted areas
- Estimate genetic diversity of targeted species in targeted areas
- Study population dynamics and population genetic structures of targeted species in targeted areas
- Study species structure and succession of the community in targeted areas
- Understand the socioeconomic effect on the conservation of *Oryza* species
- Develop conservation strategies for targeted species in targeted areas

Expected outputs
- Enhanced knowledge on population genetics and ecogeography, and community of the targeted species
- Strategies and management of targeted species designed

Activities and locations
- Conduct field survey and investigation on ecology, population dynamics
- Conduct laboratory experiments
- Locations: Hainan, Guangdong, Guangxi, Yunnan

Milestones
- By 2000: (1) complete field survey and material sampling, (2) initiate laboratory experiment
- By 2003: (1) complete field investigation and laboratory experiment, (2) propose strategies of conservation for targeted species in targeted areas

Partners
- Institute of Botany, CAS
- Institute of Crop Germplasm Resources (ICGR), CAAS
- Wuhan University, Hubei
- Institute of Crop Germplasm Resources, Guangxi AAS
- GRC, IRRI

Resources (US$)
- $475,000 for 5 years
- IRRI $100,000
- Internal cost $75,000
- Institute of Botany $155,000
- ICGR, CAAS $60,000
- Wuhan University $100,000
- ICGR, Guangxi AAS $60,000

3. Breeding new plant type rice with super high yield

Rationale

- The research has implications for meeting world food security needs in the 21st century.
- The program "Breeding new plant type with super high yield" has started at IRRI and in China.
- The program would affect about 80% of the rice-growing area in China.
- Successful cooperation between China and IRRI in this field would accelerate advancement of the program.

Objectives

- Create new rice germplasm including drought-resistant cultivars
- Breed for new plant type with super high yield

Expected outputs

- 3-5 new plant type cultivars with special characters such as huge panicles, high photosynthetic efficiency, and/or drought resistance
- 4-5 new plant type varieties with super high yield
- 5-8 published papers

Activities

- Create new germplasm by crossing between indica and japonica varieties across geographical regions or using biotechnology
- Develop new plant type varieties with super high yield through backcross or multiple cross
- Study cultural techniques which could increase yield most under local environments
- The program will be conducted in the Northeast rice-growing region (Shenyang), North China (Henan), Southwest (Yunnan), and South China double-rice-growing region (Hunan and Jiangxi)

Milestones

- Develop 4-5 varieties with yield potential 20-25% higher than popular varieties
- Early rice of double-rice-growing region: 8.5-9 t ha^{-1}
- Japonica rice in single-rice region: 12-12.5 t ha^{-1}

Partners

- Henan AAS, Jiangxi AAS, Hunan AAS, Yunnan AAS, Shenyang Agricultural University

Resources (germplasm)

- Indica and japonica varieties with good traits from Southeast Asia
- New plant type cultivars developed by IRRI
- Germplasm with special characters created by IRRI
- Upland rice germplasm from South America and Southeast Asia

Funding

- US$500,000 for 5 years
  ($60,000/year for domestic costs and $40,000/year for international costs)

4. Screening and utilization of heterotic genes in different rice groups or ecotypes

Rationale

- Hybrid rice has stagnated in yield for years
- To meet the food demand of the growing population, new approaches should be established to further improve the heterosis level of hybrid rice

Objectives

- Screen ecotypes and heterosis genes from different rice groups or ecotypes by molecular marker analysis
- Develop super high-yielding hybrid rice by using the identified heterosis genes through marker-aided selection

Expected outputs

- Heterosis genes screened in 5-6 rice groups or ecotypes such as Aus, Nuda, IRAT, tropical japonica from Latin America and Indonesia, and ecotypes from Yunnan plateau
- Several heterosis patterns established based on the heterosis genes identified

- Super high-yielding hybrid rice with 15-20% yield advantage over the existing elite check developed

Activities
- Screen heterosis genes by molecular marker analysis and establish heterosis patterns based on the heterosis genes identified
- Develop super high-yielding hybrid rice with 15-20% yield advantage over the check by using heterosis genes identified through molecular marker-aided selection

Milestones
- By 2000, identify heterosis genes in 3-5 rice groups and develop 4-6 super high-yielding hybrid rice varieties.
- By 2003, identify heterosis genes in 5-6 rice groups, develop 8-10 super high-yielding hybrid rice varieties in different ecosystems, and demonstrate and extend these hybrids by 8 million ha.

Partners
- Hunan Hybrid Rice Research Center
- CNRRI
- China Agricultural University
- Fujian AAS
- Sichuan Agricultural University

Resources
(for 6 years)
- Internal cost: US$600,000/year
- International: $300,000/year
- Training: $100,000/year

5. Selection and utilization of new sources of bacterial blight resistance in wild rice

Rationale
- Rice bacterial blight is one of the most important diseases in China and other countries, so breeding for resistance to bacterial blight is a key research work.
- Resistance to bacterial blight is one of the target characters identified by the Chinese government in releasing varieties and is an important area for resistance breeding.
- IRRI has screened some resistant wild species and bred some introgression lines which are resistant to bacterial blight. China also has abundant wild rice germplasm resources.

Objectives
- Explore and screen wild species of rice for new resistance sources and identify their genetic background.
- Use the existing introgression lines bred by IRRI in breeding for new resistant varieties.

Expected outputs
- 1-2 new genes identified from wild rice germplasm
- Use of introgressed resistance genes in rice breeding
- Use of molecular markers to identify new genetic resources
- Marker-aided breeding and cross-breeding of new varieties or lines

Activities
- Resistance screening of wild rice germplasm both in China and at IRRI
- Identifying resistance genes and breeding introgression at IRRI
- Marker-aided breeding, molecular mapping, and cross-breeding both in China and at IRRI

Milestones
- To 2000: 1-2 new resistance genes will be selected and identified.
- To 2003: new genes will be mapped and marker-aided breeding and cross-breeding of 1-2 lines or varieties will be done.

Partners
- Fujian Agricultural University
- Sichuan Agricultural University
- Wuhan University
- CNRRI
- Guangxi Agricultural University
- CAAS
- IRRI

Resources
- Total US$500,000
  (internal $250,000; external $250,000)

B. Resource Management and Social Sciences

1. Designing efficient rice farms for 21st century China

Rationale

China's general goals are to:

- Provide sufficient grain to its growing population
- Diversify its farming to meet market needs

The need to increase rice production is in an environment of declining resources (especially land, water, and labor). Given economic development, there is a need to increase profitability (to provide alternate on-farm employment) and protect the environment. Thus, rice farming for the future of China will have to incorporate labor-saving technologies, increase efficiency and profitability while diversifying to produce required market commodities, and improve quality.

General objective

- Establish high-yielding, efficient, and sustainable farms to provide diversified agricultural products

Specific objectives

- Characterize emerging rice production systems
- Design and establish appropriate farms
- Assemble and test technological options for TFM and SSCM
- Evaluate systems at a wider level

Project activities and locations

- Process-based experiments and simulation will aim to quantify water x nutrient x weed interactions
- Field monitoring and dynamic modeling
- Water balance and measurement of water productivity will be carried out at field and system levels
- Farm survey and econometric procedures
- The project will be carried out in Guangxi, Hubei, and Zheijiang

Partners

- WUHEE
- Zhejiang Agricultural University
- Chinese Center for Agricultural Policy
- Institute of Farmer Irrigation, CAAS
- IRRI
- IIMI
- Advanced research institutes in water resource management (to be identified)

Resources

(1998-2000)

- $300,000/year from China and external sources

2. Achieving economical and sustainable water-efficient irrigation in rice-based systems in China

Rationale

- The need for more rice with less water is more urgent in China than in many other Asian countries.
- Per capita fresh water availability in China is among the lowest in Asia and is still declining.
- Agriculture will be most adversely affected because of rapid industrialization and urbanization.
- China has already pioneered various strategies to achieve more water-efficient irrigation for rice-based systems.
- So far, the area where these innovations are applied is limited compared with about 3 million ha of irrigated rice-based land in China. To expand these concepts and innovations to other regions and countries, several scientific issues must be addressed.

Objectives

- Quantify the on-farm impact of water-saving innovation (WSI) practices on nutrient and weed population dynamics and pests and diseases to identify the optimum combination of water and agronomic management.
- Identify off-site impact of on-farm WSI innovations to better quantify the degree to which their large-scale adoption is leading to water savings and higher water productivity over the whole irrigation system or over a water basin.
- Assess the tangible benefits from widescale implementation of these innovations.

- Identify social and institutional arrangements that permit sustained adoption of water management innovations in areas such as Guangxi region and Hunan province.
- Accelerate the adoption of irrigation water management innovations in other rice-planting regions of China.

Outputs

- Economical and sustainable strategies and practices of water management that increase the productivity of water at farm and system levels
- Quantification of tangible economic and environmental benefits achievable from widescale implementation of the proposed strategies and practices
- Recommendations for investments and policy and institutional reforms that will facilitate implementation of water-saving strategies
- Optimum water and agronomic management systems in water-scarce conditions

3. Enhancing potassium efficiency in relation to N, Zn, and Si nutrition in high-yielding rice

Rationale

- Imbalanced fertilizer application (N:P:K ratio); dependence on fertilizer K imports
- Negative input-output balance of K and Si in rice systems
- K and Si deficiency affects N use efficiency, water use efficiency, and resistance to pests at high yield levels
    1. Apply more fertilizer (mineral, organic) or increase fertilizer use efficiency
        - Economic constraints: China 2000: import of 5 million t K fertilizer, US$2-2.5 billion per year
        - Environmental concerns

    2. Manipulate soil physicochemical properties to enhance K, N, Zn, and Si availability
        - Availability of NH_4, K, Zn, and Si depends on oxygen supply to soil and soil-root interactions
        - Manipulation through soil tillage and water management

    3. Manipulate the rice plant to obtain higher external and internal K use efficiency
        - Evidence for genotypic variation in K use efficiency in China
        - Mechanisms, traits for selection, screening techniques?

Goal

- Improve K and N efficiency and resistance to pests in high-yielding rice

Objectives

- Develop knowledge and technologies for enhancing root uptake of K in relation to N, Zn, and Si through soil, water, and crop management.
- Breed highly K-efficient high-yielding rice varieties.

Output 1 and activities

Physicochemical mechanisms determining K availability to rice roots in relation to N, Zn, and Si quantified and technologies for enhancing root uptake through soil, water, and crop management developed.

- Obtain mechanistic description of K^+ and NH_4^+ binding and transport in rice soil as affected by oxygen supply (water management)
- Quantify interactions between N, K, Zn, and Si supply and root oxidation power/nutrient uptake as affected by oxygen supply to the bulk and rhizosphere soil
- Investigate interactions between root morphology/physiology and nutrient uptake as affected by water management (superficial roots in high-yielding rice)
- Identify and test soil, 1 water, and crop management options

Output 2 and activities

Quantification of physiological mechanisms determining genotypic variation in K efficiency and breeding of highly K-efficient high-yielding rice varieties.

- Quantify magnitudes and mechanisms of variation in internal K use efficiency
- Develop/improve screening and breeding techniques
- Breed highly K-efficient high-yielding rice

Time frame

- 5 years Phase 1 — 3 years
  Phase 2 — 2years

Milestones

- 2000 Options for manipulating soil processes
  Traits and techniques for selecting K-efficient cultivars
- 2002 Soil and water management technologies for enhancing K, N, Zn, and Si efficiency
  K-efficient high-yielding rice varieties

Partners

- ZAU (soil chemistry and plant nutrition)
- CAAS (plant physiology and screening)
- CNRRI, Hangzhou (breeding)
- IRRI and University of Hohenheim, Germany

Funding

- About US$200,000-300,000 per year
- Substantial training and scientists exchange component

Linkages

- China-IRRI projects on water productivity and optimal farm management

C. Pest Management

1. Relationship between pesticide use and insect problems under high-yielding production systems in China

Rationale

- Brown planthopper (BPH) is considered the major insect problem in the high-yielding production system in China.
- Current control practices involve frequent pesticide applications with negative effects on the environment and human health.
- Although an integrated pest management approach aimed at reducing pesticide use is in place in the tropics, a similar strategy has not been tested in the high-yielding production and temperate environment in China.

To formulate an IPM strategy, a number of questions need to be addressed. Does the intensive production system need more pesticides? Are the current pesticide applications necessary?

- This proposal aims at generating answers to these questions and developing IPM strategies appropriate for the production system in China.
- The initial target is BPH due to its perceived importance; however, the information generated is expected to be applicable to the management of other insects.

Objectives

- Determine whether overuse of pesticides is responsible for the continuing problem of BPH and some other insect pests in the high-input production system in China.
- Determine if there are other abiotic factors contributing to BPH/insect problems:
  - Where in China is BPH most serious?
  - Under what condition(s) is BPH serious?
  - How frequent do outbreaks occur?
- Develop alternative tactics to manage BPH and other insect outbreaks.

Expected outputs

- Real pest problems determined in response to the current and future rice production system
- Insecticide misuse and impact of areawide insecticide use pattern defined
- Causes of BPH problems defined
- Insecticide use under high-yielding conditions understood and rationalized
- Enhanced IPM technology and strategy in China
- Decreased amount of pesticide used, less damage to the environment, and simple ways for farmers to decide on pesticide use developed

- Strategies and methods to improve pest management developed

Activities

- Establish patterns of pesticide use in affected provinces (already done in many places, no need to repeat if data are available)
- Determine whether current farmers' practices in pesticide use are ecologically and economically appropriate
- Determine the impact of insecticide sprays on ecological fitness of pest species (e.g., BPH, WBPH)
- If pesticide use is the cause of continuing insect problems, develop alternative management strategies in the high production environment in China

Milestones

- 2000
  - –Real insect pest problems determined in response to current and future rice production in China
  - –Impact of area wide insecticide use pattern and cause of BPH problems defined
  - –Insecticide used under high-yielding production systems rationalized

- 2003
  - -IPM technology and strategy enhanced in China
  - –Strategy and methods to improve insect pest management developed
  - –Amount of insecticide use decreased and impact on environment documented

Partners

- Zhejiang AAS
- Hunan AAS
- Sichuan AAS

2. Integration of host plant resistance (transgenes) and biological control for sustainable management of rice sheath blight

Rationale

- Sheath blight caused by *Rhizoctonia solani* AG 1 is the leading cause of yield loss in the high rice production system in China.
- For the last three decades, it has been controlled by a very effective fungicide, Jinggangmycin. In recent years, due to the gradual increase in tolerance shown by the fungus pathogen, the dosage of Jinggangmycin has doubled.
- Reliance on chemical control of a single fungicide is often inadequate and ineffective.
- So far, there has been little success in identifying a usable level of host plant resistance that can be incorporated in the breeding program. Consequently, most cultivars grown in China show a very low resistance level to sheath blight, especially in the high-yielding production system.
- Multiple approaches are needed to address this problem to reduce fungicide use and production cost based on sustainable disease management.
- Enhanced sheath blight resistance has been demonstrated in transgenic rice containing cloned defense genes under greenhouse conditions.
- Rice ecosystems, both in the tropics and temperate zones, have supported abundant antagonistic bacteria. Many of them are broad-spectrum and can suppress the development of more than one disease in rice plants and also promote rice crop growth through seed bacterization. They show potential for disease management, an area that is highly relevant to China where chemical control is very often the only option for disease control.
- A combination of transgenic and biocontrol approaches offers new opportunities to manage sheath blight in a sustainable manner.

Objectives

- Determine whether the fungicide use pattern is appropriate for managing sheath blight
- Reduce sheath blight damage using
  - –Host defense genes through transgenic plants
  - –Indigenous biological control agents (mainly antagonistic bacteria)
  - -Cultural practices (nitrogen application, planting density, "canopy" management)

- Develop a supply and demand system to scale up the application of biological control technology for rice production

Expected outputs
- Documented information on tolerance (qualitative or quantitative mechanism) of *Rhizoctonia solani* AG 1 for Jinggangmycin
- Protocol of evaluating transgenic rice plants with defense genes for sheath blight resistance developed and tested
- Screening strategy designed to isolate and identify efficacious biocontrol agents for sheath blight under high-yielding production system
- A delivery system of biological control developed and tested
- Integration of potential rice plant with transgenic and promising biocontrol agents under high-input system tested

Activities
- Determine the nature of Jinggangmycin resistance from isolates of wide geographical areas and develop methods to assess tolerance (quantitative resistance) for Jinggangmycin
- Design a protocol for field evaluation of transgenic rice with defense genes for sheath blight resistance
- Evaluate a delivery system of biocontrol agents
- Determine feasibility of integrating transgenic plants with biocontrol agent for sustainable sheath blight management

Milestones
- 2000
    1. Jinggangmycin-resistant *R. solani* AG 1 strains determined from field population
    2. Field evaluation protocol for transgenic rice with chitinase for sheath blight resistance established and tested
    3. Methods to evaluate rice-associated antagonistic bacteria for sheath blight control developed
    4. Formulation of local BCA strains tested at key sites in different provinces
- 2003
    1. Transgenic rice with chitinase for sheath blight control tested in the field following the protocol
    2. A delivery system of biological control technology linking farmers, county agents, and researchers established and in place for rice production
    3. Potential of an integrated approach to sheath blight control using transgenic rice with chitinase and BCA documented for rice production

Partners
- Jiangsu AAS
- Anhui AAS
- Zhejiang Agricultural University
- Jiangxi AAS
- Sichuan AAS
- Fujian Agricultural University

3. Germplasm diversification and gene deployment for disease control

Rationale
- Rice blast is considered the top production constraint in both subtropical and temperate environments in China.
- Currently, cultivars with good yielding potential and high grain quality often lack blast resistance.
- There is also a general concern that resistance genes are often used over a large area. This genetic vulnerability could be exacerbated by the increased area of hybrid rice.
- There is a need to (a) identify good sources of resistance and (b) diversify resistance sources incorporated into cultivars and deployed in the field.
- The genetic make-up of pathogen populations varies in different provinces; thus, there is a need for a coordinated program to introduce diverse resistance genes (both qualitative and quantitative type) into local high-yielding and high-quality rice cultivars.

Objectives

To avoid the rapid breakdown of resistant cultivars, a systematic approach to identify good resistance sources and to understand host-pathogen coevolution in the major rice-producing provinces in China is essential. A multiple-component research that uses available expertise and genetic resources in participating institutes is suggested. Many individual components are probably already in place; nonetheless, it is felt that a China-IRRI initiative to focus on this problem can lead to better coordination of research efforts and accelerate the identification and deployment of effective resistance sources in the field. The overall objectives of the initiative are to:

- Develop high-yielding and high-quality cultivars with durable blast resistance adapted to local conditions of different provinces in China
- Promote collaboration among local institutes to:
  - –share database on resistant germplasm
  - –share database on pathogen populations at the regional level
  - -exchange mapping populations for genetic analyses
  - -evaluate advanced elite lines

Expected outputs

- An accessible database on blast resistance of rice germplasm
- An accessible database on virulence spectrum and genetic relationship of blast pathogen populations at the provincial level
- Selected major genes and QTL mapped onto rice chromosomes, which will serve as a nationwide genetic resource for marker-aided breeding
- High-yielding and high-quality cultivars or elite lines with diverse sources of blast resistance developed
- Established collaboration among laboratories with a mandate on blast control

Activities

- Establish a database of traditional or advanced lines with demonstrated durability in blast resistance (both qualitative and quantitative genes)
- For each participating institute, identify the best resistance sources for local breeding. The resistance sources can be evaluated and shared among participating institutions and provinces
- Use several mapping populations (existing or to be generated) to identify chromosomal locations of resistance genes (major genes or QTL)
- Each institute continues the incorporation of diverse R sources into local high-yielding and high-quality rice with the aid of genetic markers shared among institutes
- Collaborate in evaluating advanced materials for blast resistance at multiple locations
- Collaborate in characterizing the pathogen population structure at the regional level
- Deploy these lines over blast-affected areas based on an understanding of local pathogen populations

Milestones

- 2000
  - –Database on virulence spectrum and genetic relationship of blast pathogen populations at provincial level

- 2003
  - –Major genes and QTL mapped onto rice chromosomes used as a genetic resource for marker-aided breeding
  - –High-yielding and high-quality breeding lines with diverse sources of blast resistance developed

Partners

- Chinese AAS
- Guangdong AAS
- Jiangsu AAS
- CNRRI
- Zhejiang Agricultural University
- Huazhong Agricultural University
- Yunnan Agricultural University
- Fujian Agricultural University

ANNEX 3
Strategic research and capacity building in China

Cheng Xu
Director General, Dapartment of Education, Ministry of Agriculture, China

Agricultural research in China must focus on the development of key technologies in 10 priority areas identified in China's Ninth Five-Year Plan (1996-2000).

1. Use of Germplasm Resources for Breeding

Evaluation, development, and application of germplasm resources of animals and plants for breeding based on integrated evaluation, genetic analysis, and artificial improvements.

China has collected and preserved more than 300,000 samples of crop varieties in the genebank for breeding.

Important traits are pest resistance, quality and nutrition value, plant growth type, growing period, and QTLs.

Typical examples for livestock germplasm are prolificacy gene, the delicious taste of chicken meat, and tolerance for harsh feeding.

Difficulties to overcome
- effective methods of quickly identifying and appraising traits
- effective ways of marker-aided breeding

2. Crop Breeding and Use of Crop Hybrid Heterosis

Selection for new species and varieties of animals and plants. This research is focused on rice subspecies crossbreeding between japonica and indica types, as well as "super yield" breeding technology, "two-line breeding" of hybrid rice, "three-line breeding" of hybrid wheat, selection for maize inbred lines with high combining ability, and cotton breeding for insect resistance.

Institutes that are financially supported by the Government conduct research on more than 400 breeding projects. They have succeeded in innovating dwarf high-yielding rice varieties, higher yielding maize hybrids with upright and straight leaves, semidwarf wheat cultivars with resistance to diseases such as rust, as well as higher yielding cotton (ginned cotton: 3 t ha^{-1}). China was the first to exploit hybrid heterosis in rice.

Some encouraging breakthroughs are
- Chinese "super rice"
- Hybrid wheat using "three-line'' or chemical hybridizing agent (CHA) method
- Special maize hybrids adapted to Southern China's mountainous conditions (acid, barren soil and periodical droughts)
- Hybrid cotton (three-line)

Difficulties to overcome include
- Need for new inbred lines for maize that are genetically distant from current lines and with a higher combining ability.
- For more effective and profitable hybrid wheat seed production, a new CHA is urgently needed.
- Identification of genetic background of subspecies crossess of rice.

3. Plant Protection and Veterinary Science

Technologies on animal and plant disease and insect control. Improvements in monitoring for chemical pesticide resistance of insects, etc.

Problems

- Some diseases have become major ones with the rise in yield level.
- "Conventional" pests build up due to poor crop rotations.
- Some pests are becoming increasingly resistant to pesticides, worsening the pesticide residue problem.
- Weak capability in formulating new pesticides.
- The industrial manufacture of biological control agents is still limited.
- Outbreaks of contagious diseases of livestock have occurred frequently, mainly due to increased confinement feeding.

Key issues to be solved

- Application of molecular pathology
- Innovation of mimicking herbal biopesticide
- Establishment of biocontrol agent industry
- Popularization of feasible specific pathogen-free technology

4. Comprehensive Technologies for Higher Yield, Superior Quality, More Profit, and Less Labor

Comprehensive technology system for high yield, high quality, and more profit. Special attention will be paid to the eradication of obstacles that limit yield, such as salinity, drought, low fertility, and waterlogging.

Requirements

- Specific technologies for producing nonpolluting agricultural products and recovery of plastic film that is used in almost every aspect of agricultural production
- Technology and equipment for artificial rearing of seedlings and transplanting, especially for maize, cotton, etc.
- Highly effective machinery adapted for raising cropping index
- Technology for labor-saving cultivation
- Quality standardization for agricultural produce

Specific technologies are required for erosion-prone and semiarid mountainous land; saline-alkaline and secondary salinization land; red, yellow, and yellow-laterite soil; and dryland farming area.

5. Biotechnology and Gene Engineering

Agricultural biotechnology and its application and commercialization. Virus-free, disease-, and insect-resistant crops and animals. Gene engineering for pest resistance breeding and quality breeding.

This area provides China with excellent possibilities to make full use of its unique and ample crop and livestock germplasm. Some of the problems in this area include:

- Dispersed, small-scale work and lack of organization and coordination
- Lack of fundamental research on areas such as genome and gene mapping
- No rational mechanism to integrate biotechnology and genetic engineering with conventional techniques such as conventional breeding
- Difficulty in establishing a high-tech industry based on biotechnology and genetic engineering

6. Postharvest Science and Technology and Food Science

Technologies for improving postharvest storage and processing of agricultural products to get value-added effects.

One of the fundamental causes of China's poor performance in these areas is that some leading research organizations consider these as tasks of institutes which belong to the Ministry of Light Industry or the Ministry of Commerce. Agricultural research institutes should take charge of work in these fields.

There are many potential gains from research in postharvest and related issues. Through value-added processes, the status of agro-produce can be elevated to "food" commodities, and thus profit margins in agriculture can be improved and agriculture's image as a low-profit enterprise can be enhanced.

7. Feed Science and Animal Nutrition

Technologies on feed development aimed at improving the feed conversion ratio.

The availability of agricultural feed is becoming increasingly important. However, research on, and production of, feed additives is insufficient. Forage technology research lags behind. Unlike in the US, medium and small feed enterprises will continue to dominate the market in China due to the longevity of the "family system.''

8. Technologies of Sustainable Agriculture

Sustainable and intensive production technologies on agriculture, especially those for artificially controlled cultivation environments.

The conservation of resources and the environment is essential and must become an integral part of agricultural production in China. Intensification of agriculture in a sustainable way needs to rely primarily on the increased use of human capital and talent. Technical innovations are required in the following fields:

- Reducing the impact of natural calamities
- Providing information on biotechnology issues
- Applying biotechnology tools
- Decreasing and preventing pollution
- Using chemical hybridizing agent technology and ecological engineering
- Applying environment-controlled farming
- Attaining higher efficiencies of physical inputs for agriculture

9. Regional Comprehensive Rural Development

Regionally integrated environment.

Emphasis should be on alleviating poverty, the main problem in many rural areas. There is a critical need to:

- Diagnose obstacles in development and work out strategies based on systematic survey and evaluation
- Set up development programs and plans that include leading industries
- Tap and organize labor, capital, and knowlege
- Extend technologies and solutions to critical technical issues
- Raise funds and improve management, credit, and cooperative society system
- Explore the market
- Look into incentives and restraint mechanisms

10. Raising Efficiencies of Agricultural Inputs

Higher efficiency of resource application, and development of protection technologies on agricultural environment and resources.

The main components are:

- Chemical fertilizer
  - there is a demand for "specific consultant" system
  - the concentration of active ingredients needs to be increased in most products on the market
- Water resources
  - available technologies and equipment do not fit China's requirements
- Pesticides
  - China needs "field schools" for extension
- Fuel and power
  - the performance of agromachinery needs to be improved
  - alternative energy needs to be tapped
- Seed
  - seed industry is weak and research in seed science is still not established