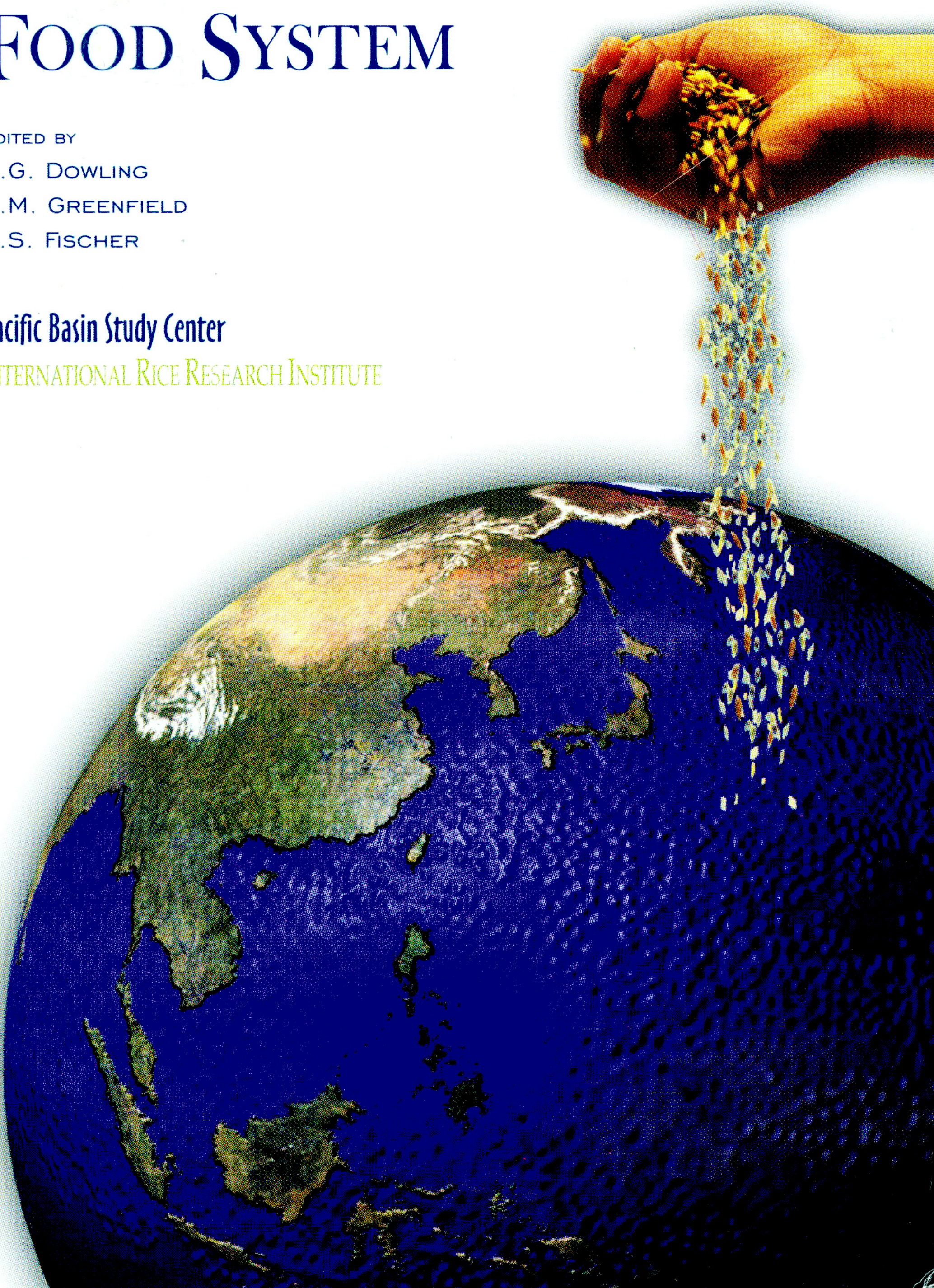
# SUSTAINABILITY OF RICE IN THE GLOBAL FOOD SYSTEM

EDITED BY
N.G. DOWLING
S.M. GREENFIELD
K.S. FISCHER

Pacific Basin Study Center
INTERNATIONAL RICE RESEARCH INSTITUTE



# Sustainability of Rice in the Global Food System

Edited by
N.G. Dowling
S.M. Greenfield
K.S. Fischer

1998
Pacific Basin Study Center*
International Rice Research Institute

*Now part of the East Asia Center on Population, Resources, and Welfare—EACOPRAW—at the University of California, Davis

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 16 nonprofit international research centers supported by the Consultative Group on International Agricultural Research (CGIAR). The CGIAR is cosponsored by the Food and Agriculture Organization of the United Nations (FAO), 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, and Rockefeller Foundation, and the international aid agencies of the following governments: Australia, Belgium, Canada, People's Republic of China, Denmark, France, Germany, India, Indonesia, Islamic Republic of Iran, Japan, Republic of Korea, The Netherlands, Norway, Philippines, Spain, Sweden, Switzerland, United Kingdom, and United States.


Los Baños, Philippines
Mailing address: P.O. Box 933, Manila 1099, Philippines
Phone: (63-2) 845-0563, 844-3351 to 53
Fax: (63-2) 891-1292, 845-0606
Email:IRRI@CGIAR.ORG
Telex: (IT) 40890 Rice PM; (CWI) 14519 IRILB PS
Cable: RICEFOUND MANILA
Home page: http://www.cgiar.org/irri
Riceweb: http://www.riceweb.org
Riceworld: http://www.riceworld.org
Courier address: Suite 1009, Pacific Bank Building
6776 Ayala Avenue, Makati
Metro Manila, Philippines
Tel. (63-2) 891-1236, 891-1174, 891-1258, 891-1303

**Suggested citation:**
**Dowling, NG, Greenfield SM, Fischer KS, editors. 1998. Sustainability of rice in the global food system. Davis, Calif. (USA): Pacific Basin Study Center, and Manila (Philippines): International Rice Research Institute. 404 p.**

EDITORS: Bill Hardy, Domenic Fuccillo
DESIGNED&PRODUCEDBYTHECPSCREATIVE&PRODUCTIONTEAM
COVER DESIGN Juan Lazaro IV
COVER PHOTOGRAPHY: Lingkod Sayo
COVER CONCEPT AND ART DIRECTION: Albert Borrero
DIGITAL IMAGING: Raul Ramiro Jr
PAGE MAKEUP, ARTWORK, AND COMPOSITION: Erlie Putungan
PRINT PRODUCTION MANAGEMENT Millet Magsino

**ISBN 971-220-107-4**

# Contents

# Preface

Rice is the primary food grain consumed by almost half of the world's population. During the past half century, rice has become available to consumers on increasingly favorable terms. Rice yields have risen more rapidly than demand arising out of population and income growth. These gains have resulted from the development of new and more productive rice varieties, increased intensity of fertilizer use, expanded irrigated area, improved crop protection, and the development and use of better management practices by agronomists and farmers.

The success in generating rapid growth in rice yields, often referred to as the Green Revolution, has given rise to excessive complacency on the part of national governments and international aid agencies. While yields have continued to rise at the farmer level, maximum yield in trials at the International Rice Research Institute (IRRI) and at other leading rice research centers has remained static for almost two decades. Does this imply a new biological ceiling on rice yields that will limit them to the 8–10 t $ha^{-1}$ now being achieved by the best farmers in the most favored rice-growing areas?

This concern has led to a new and broader rice research agenda, focusing on the new possibilities being opened up by advances in molecular biology and genetic engineering for plant breeding and crop protection. Researchers are working to develop knowledge-intensive farming systems, and attempting to ensure the conservation of rice germplasm diversity and to expand the use of underexploited relatives of cultivated species.

This book represents the best single source of knowledge available on the state of efforts to develop the scientific and technical basis for a second Green Revolution—for the advances necessary to sustain the increases in yield that have been achieved in the past and that will be needed to meet the demands that consumers will place on the world's rice farmers in the first half of the 21st century.

V.W. RUTTAN

CHAPTER 1

# Introduction and overview

S.M. Greenfield and N.G. Dowling

Over the past decade, increasing concern has been expressed about “global sustainability” and “sustainable development.” Although sounding somewhat similar, these terms do not, at least initially, cover the same areas. Global sustainability involves the sustainability of the world’s institutions that are dedicated to meeting the needs of rising demands for goods and services in the face of changes in the natural environment. Sustainable development involves the ability to sustain the course of global development vis-à-vis the need to protect the environment, ecosystems, and the world’s population. Obviously, these concerns merge when the drive to sustainably develop any one sector reaches a point where an unacceptable restraint jeopardizes its continued viability. The importance of understanding and ultimately ensuring the sustainability of the world’s societal institutions in the face of increasing developmental pressure and natural changes is well recognized. Also recognized is the fact that information deficiencies and the complex nature of the problem severely limit our ability to intelligently address alternative strategies for avoiding a potentially deleterious future.

This subject has been under discussion at the Pacific Basin Study Center for a number of years as a search was made for an approach that might help solve the problem. We realized that although the ultimate objective would be to address the question of global sustainability, reality—in the form of the recognized complexity of the subject, little understood interrelationships and feedback mechanisms, and inadequate databases—dictated the need to first scale the problem appropriately.

Stated another way, sustainability involves the continued ability of our societal institutions to meet the current and future needs of their client populations. Achieving sustainability also requires that we meet these needs without compromising the ability of future generations to meet their own socioeconomic needs. When we attempt to address the question of global sustainability, we immediately realize the complexity of the problem, particularly if we are determined to deal with the entire mix of institutions that define human interactions with the planet. To avoid many of these complications, we chose to first focus on the single issue of agriculture and, in particular, the problem of sustainable rice production and distribution. This decision was based on the fact that most of the problems involved in striving to understand the global sustainability macrocosm, particularly when confronting the uncertainty of potential global change, are present when we study the agricultural sector and food security. Further, the quasi-global characteristics of rice production and distribution provide a microcosm of the macro issues that we must address. Because of the relatively rich research base on rice, an examination of the crop, from production through consumption, should shed light on the important interacting roles played by technical, climatic, cultural, ecological, economic, social, religious. political, and geographical factors and their temporal and spatial variations. In addition. such an investigation, if structured correctly, should provide some insight into potential policy options for use globally and locally.

This potential to provide insight into impact is clearly illustrated when we consider the current and projected situation for rice production and consumption worldwide. Rice provides about 40–45% of the calories consumed in the Pacific Basin, and as much as 70% in Vietnam, Cambodia, and Bangladesh. Rice is one of the world's primary food crops; 90% of the world's rice is grown in Asia, and almost all of it is consumed there—a third in China and a fifth in India. Without considering substitute foods, rice production must grow 60% by the year 2020 to keep pace with Asia's increasing population (*IRRI Toward 2000 and Beyond,* International Rice Research Institute, 1989). The amount of land available for cultivated rice production is not increasing, partly because of the urbanization of the world's population. It has been estimated that up to 85% of all arable land in Southeast Asia is currently under cultivation. Therefore, to meet the projected demand, a 3% increase in yield per hectare per year on the remaining arable land is needed. But recent studies indicate that such an increase is unsustainable: in fact, yields in many areas are declining, despite the use of chemical fertilizers and pesticides. New rice varieties, through genetic engineering, mechanization, and a better understanding and use of soil chemistry, may be useful for increasing yield. Other important considerations involve ideal farm size, economies of scale in differing regions, and the social dislocation that would result from any large change in existing systems.

In addition, because of rapidly escalating populations in Asia and the region's apparently limited ability to increase rice production to meet the growing demand, sustainability of this crop must clearly be considered, almost from the beginning, on a more global basis. In particular, the rice-producing capacity of the United States and its ability to adjust to an expanding demand can become a key factor in determining the security of this important food product.

The complex nature of the problem described is clear. Any attempt to seek understanding and, ultimately, strategies to deal with such a problem must first address the need to integrate the input of the many disciplines involved in considering both technical and policy issues. This integration provides a way to achieve a common language and effective method of communication among participants, and promotes a strong inter- and intradisciplinary interaction.

To date, the problem of sustainability at any institutional level has not been adequately structured and defined to the point where we might expect the required integration and interaction to occur. But we are not implying that the problem is not recognized. The United Nations Food and Agriculture Organization (FAO) and the United Nations Development Programme (UNDP), for example, have shown a growing interest in global food security and have held numerous conferences on the subject. They organized an international food summit, held in Rome in November 1996. Although such activities are crucial to alerting and sensitizing decision makers to the magnitude of the problem, they must be supported by in-depth studies designed to provide the understanding and analytical tools needed to explore alternative strategies that could help mitigate the problem.

The first steps must be ones that help to:

- define the problem (in this case, sustainability of rice as a viable part of the food chain) and its complex aspects (i.e., technical and policy),
- develop a set of realistic scenarios,
- explore the ability to simulate these scenarios, and
- determine the limits of our knowledge and information and hence the next steps that must be taken to remove these limitations.

If we design an effective integrated approach to address the problem, then we will be well on our way to taking these four steps and, more importantly, the desired interaction and integration will have started and effective communication will be established. This international network of people can begin the process of sharing information and understanding that can ultimately lead to the development of effective strategies and policies to allow the world to cope with the problem of sustainability.

What was obviously required to carry this out was a cost-effective process whereby interactions

- would occur over a vastly extended time period,
- would not require participants to participate continuously, but would allow them to leave and reenter the "discussion" and still have a sense of what occurred during their absence,
- would ultimately provide easy and convenient access and involvement for policy- and decision makers, and thus provide an ongoing forum that would serve as a resource and "sounding board" as ideas surfaced, conclusions were reached, global and local policies were developed and decisions formulated, and
- would provide a semipermanent communication network of the disciplines involved that would allow the rapid exchange of information and ideas, and encourage collaborative efforts to address the issues involved.

The approach adopted drew upon rapidly developing Internet/World Wide Web capabilities to establish a relatively permanent international electronic network that could grow and promote, among a broad set of participants, the desired interaction and exchange of ideas and information. Via this approach, papers were prepared, distributed, and commented on, and ideas were exchanged and discussed. In addition, participants believed that information could be exchanged; electronic conferences held; questions raised, discussed, and answered; simulations tried; and scenarios, strategies, and policies developed, explored, and placed before decision makers.

All the participants believed strongly that the use of such a network could promote an international common purpose and could allow all participants to express their concerns and have them considered within the context of the whole. This could help solve some policy problems before they became insurmountable. In essence, we can view this approach as a phased effort imbedded in an ongoing, interactive Web forum.

The purpose of what was essentially the first phase of a long-term effort was to set up and begin the crucial dialogue among participants that would ultimately result in a working forum capable of addressing complex technical and policy issues. The objectives of this phase were as follows:

1. Demonstrate how rice sustainability represents a microcosm of global food security.
2. Place rice production within the context of the general food system (define).
3. Begin developing the understanding that underlies an ability to provide the advice required for decisions in response to perceived problems under a broad range of potential scenarios (optional choices, "societal costs," problem avoidance vs. the search for "permanent" solutions, economic viability, etc.).
4. Explore where and how these elements come together in the pursuit of research and informational needs and policy options.
5. Begin the effort to determine what we must know to permit a timely analysis of sustainability in contrast to our current knowledge.

The process through which these objectives were addressed is represented by a group of commissioned papers designed to stimulate discussion. These papers, carefully chosen to provide a spectrum of current thinking, were prepared under an NSF/EPA (National Science Foundation/Environmental Protection Agency) grant. Abstracts were made available on a Web page specifically designed for this conference and made part of the Conference on the Web (COW) procedures with software developed and implemented by San Francisco State University.

With the COW software, access to this Web page was limited to those invited to participate in the conference (see the list of participants in Appendix 1). All participants had the ability to download any of the full papers they desired to read and critique.

Over a specified time period, the invited participants had the opportunity to submit comments or supplementary materials on any of the papers (or subjects represented by the papers) available through the conference Web page. Comments submitted through COW were available to all conference participants, who could thus make their own papers or data available to each other.

This book contains all of the papers prepared for this first Web conference on the sustainability of rice production. As such, it represents not just a collection of the originally commissioned papers; it also contains the final version of these papers as modified by the comments and dialogue of the participants. This book could be viewed as the first volume of a series that begins by exploring the technical and socioeconomic aspects of a global problem, including a sense of what is known now and a research agenda designed to close the existing information gap. Whether subsequent volumes are prepared will depend on how seriously the problem is viewed by global decision makers. Whether or not these subsequent volumes are ever prepared, these same decision makers and people around the world will ultimately "write" the final volume.

The overall objective of this book is to examine rice production from many aspects of the rich academic and policy base, not only from the side of production and economics but also from the involvement of generations of people of many cultures. Professor Vernon Ruttan, well known for his involvement in international agricultural policy, provides a preface and evaluation of the volume. James Gustave Speth, director general of the UNDP, which together with the FAO sponsored the United Nations Conference on Food Security in November 1996, explains the international concern about the growing world population and declining food supplies, especially in countries with the lowest average annual incomes. These include some countries in Asia and Africa that need attention to policies and research to provide a sustainable food supply.

In the part of the book dealing with food systems, Hossain considers the important aspects of the food supply: (1) water, land, and labor scarcities, (2) the importance of rice in the diet, (3) the cost of growing rice and the impact of income production, and (4) the greater dependence of poor countries on rice. This chapter points out the need for improved farm management, mechanization, and help in developing nonfarm employment. The General Agreement on Tariffs and Trade (GATT) may pressure high-income countries out of rice production and favor poor countries such as Vietnam. Demand for rice in high-income countries will decrease, whereas in poor countries, where population will increase, demand for rice will increase (such as Vietnam and Pakistan, among others).

Bray presents three cases—from late imperial China, contemporary Vietnam, and contemporary Japan—to illustrate the potential of small-scale wet-rice farming as a sustainable basis for a diversified rural economy. She concludes that planners must find ways to strengthen rural economies and increase both food output and the numbers of people to whom the local economy can provide a livelihood.

Dahlberg examines the elements for maintaining a sustainable rice system and developing a larger framework and structures of regenerative food systems. The nature and structure of regenerative food and fiber systems are evaluated based on the health and regenerative capacities of biological and social systems. This framework is then applied to historical and current rice cultures to understand how rice fits into efforts to create more sustainable food systems. Some future research questions are raised.

Parts III and IV, which deal with rice production systems, are a compilation of papers prepared by specialists in rice at the International Rice Research Institute. These papers were specially prepared for this book and they cover diverse scientific subjects. These papers present current and pending research on the sustainability of rice in the food supply over the next 30 years. Each paper suggests the most important questions that must be addressed in that field.

Part III contains nine chapters:

- Fischer explains the overall picture of rice in the Asian region.
- Peng and Senadhira review the genetic development of rice since the Green Revolution and analyze aspects of plant development that are being studied to improve the nutritional value of the plant.
- Reichardt et al present soil nutrient conditions in both wet-rice and dry-rice regimens. Rice grown in flooded fields produces higher yields, but most of the world's rice is rainfed. Because water is a scarce resource, some areas have potential for intensified crop production.
- Cohen et al examine work in progress to quantify risk probability and risk magnitude of damage to crops from insects, plant diseases, and weeds.
- Olofsdotter et al show the importance of developing integrated weed management systems in which several control measures are combined and herbicide use is minimized.
- Bhuiyan et al analyze how water management and rice production systems can be improved to obtain more rice per unit of water supplied.
- Price and Balasubramanian address the need for knowledge-intensive resource management encompassing "smart" equipment and increased information to farmers to improve production and environmental quality.
- Wassmann et al examine the key effects of agricultural production on the environment, including the benefit of increased $CO_2$ for rice yield and the effect of methane emission from rice.
- Bennett et al discuss research strategies to enhance rice plants through $N_2$ fixation, apomixis, and perenniality. They conclude with an overview of the challenges to achieving higher rice yield from the perspectives of systems analysis and mathematical modeling.

Part IV addresses the use and conservation of biological diversity for agroecosystems, especially rice. It also describes the use and management of genetic diversity of the rice gene pool and the indigenous biota of rice landscapes.

- Fischer analyzes the importance of biodiversity to the sustainability of rice.
- Bellon et al investigate the threats and challenges that the conservation of rice genetic diversity faces from changing socioeconomic and cultural conditions, as well as from the development and widespread adoption of modern varieties.
- Schoenly et al explain the rich biodiversity of microbial, floral, invertebrate, and vertebrate populations found in tropical rice fields. The challenge is to find the best ways to inventory, characterize, and assess such diversity and interconnected communities.

Part V addresses economic considerations.

- Evenson looks at the major features of the genetic improvement of rice and review studies that attempt to value rice genetic resources. He assesses the comparative role of genetic improvement and its prospects in the Second Green Revolution.

- Smil analyzes the contradictions in rice agriculture, from the declining use of rice in richer Asian diets to the growing demand for rice from the increasing population. The environmental benefit of rice production for paddy biodiversity may outweigh the negative impacts of nitrogen and methane buildup.

Part VI features two case studies.

- Lin presents a country case study of rice yield under field conditions in China. He compares actual yield with experimental plot yields that indicate a higher yield potential, based on genetic differences as well as natural conditions (weather, soil, etc.).
- Paroda examines the complex efforts in India to support the infrastructure for increasing rice yield and improving socioeconomics and policies for food security. India needs to increase rice productivity by 3% annually, by using technology, increasing genetic yield, and exploiting abundant untapped opportunities in the rice environment.

The final chapter summarizes the research questions raised by the authors. Many of these questions are already being examined. A case is made for an integrated approach and understanding that could ultimately permit us to rationally address potential solutions to the problem of sustainability.

Because of the ongoing, dynamic nature of this project, the editors would appreciate any constructive suggestions or comments from interested readers of this initial volume.

## Notes

*Authors' addresses:* San Francisco State University, San Francisco, California. sgreenfield@earthlink.net and nrmoini@earthlink.net

*Acknowledgments:* The framework of this effort was based on the work of a steering committee chaired by William Rains. Members were Richard Howitt, Peter Lindert, and Shu Geng of the University of California, Davis; Kenneth Fischer of the International Rice Research Institute (IRRI); Kenneth Dahlberg, Western Michigan University; and Stanley Greenfield and Noreen Dowling of the Pacific Basin Study Center. IRRI gave staff members time to prepare several papers presented here and its Communication and Publications Services helped edit and print this book. Ronald Miller persevered in elaborating the Web site and Donya Khalife helped prepare the papers for this publication. Funding for this effort was provided by the National Science Foundation in conjunction with the United States Environmental Protection Agency under NSF/EPA grant number 9602476.

We also wish to thank the following reviewers for their contributions: Stephan Brush, Colin Carter, Shu Geng, Daniel Sumner, and Edward Taylor, University of California, Davis; J. Berkowitz, University of Connecticut; and Kenneth Cassman, University of Nebraska.

*Citation:* Dowling NG, Greenfield SM, Fischer KS, editors. 1998. Sustainability of rice in the global food system. Davis, Calif. (USA): Pacific Basin Study Center, and Manila (Philippines): International Rice Research Institute.

# Part I:
# Food Security

CHAPTER 2

# Global food needs and resource limits

J.G. Speth

Rice, the staple food for the largest number of people today, is important for development. We have learned much about the potential of agricultural technology from work in rice, and it is in the area of rice that the most striking growth has taken place.

## Food supply: growth and crises

Breakthroughs in cereal technology have helped to increase grain production. The production of 10 major food crops in developing countries increased by 74% in the past two decades, with yield advances from technology contributing to 70% of this growth in output. Investments in agricultural research at the Consultative Group on International Agricultural Research (CGIAR) centers and in national research and extension systems have been instrumental in this increased productivity.

Developing countries use high-yielding varieties on 74% of the area producing rice, 70% of wheat area, and 57% of maize area. Food grain availability has been increasing and, according to the International Food Policy Research Institute (IFPRI), 150 million fewer people go to bed hungry than 25 years ago, and an additional 1.5 billion people in developing countries are being fed with the incremental production.

The availability of staple food has grown in all regions of the world except sub-Saharan Africa, where this remains a critical concern. There, population growth has outstripped growth in agricultural production. Food imports rose by 185% between 1974 and 1990, and food aid by 295%.

## Food for sustainable human development

Too often, agriculture and its development have been perceived in narrow food-supply terms alone. Technical specialists in agriculture can contribute to increasing production potential, output, and efficiency. But the social, institutional, and policy dimensions are critical in translating scientific knowledge into the reality of fuller lives. These dimensions have been much harder to address as effectively as have scientific developments.

The focus of attention should shift from the world's food needs to people's food needs. The world's food needs are primarily driven by market prices, and an abstract unfulfillable goal, whereas people's food needs are a more tangible fulfillment of needs for a healthy life. Sustainable food security is a fundamental aspect of sustainable human development. It fuses the goals of household food security and sustainable agriculture. A commitment to sustainable food security requires that we address not only increasing agricultural production but also income and land distribution, dietary needs, women's status and opportunities, and the protection and regeneration of the resource base for food production. The recent World Food Summit held at the Food and Agriculture Organization of the United Nations (FAO) has clearly emphasized the more people- and environment-oriented approach to guide future investments.

## Food strategy for sustainable human development: three policy areas

We can identify three components of the sustainable human development approach, as it relates to food and agriculture: food and participatory development, food and environmental sustainability, and food and sustainable livelihoods.

### Food and participatory development

Broad-based economic growth that is equitable and anticipatory is central to eradicating poverty and meeting food needs. Agricultural development is an important instrument for this growth, but only insofar as it is accompanied by dynamic nonfarm economic growth. The United Nations Development Programme's (UNDP) Poverty Strategy Initiative, through participatory methods, helps smallholders and communities identify and implement a range of actions to improve their livelihoods.

Though the rural poor are immensely skilled in generating livelihoods under adverse conditions, they mostly operate with no improved inputs or information, low prices and distant markets for their produce, and virtually no institutional support for harnessing and managing natural resources. Migration to cities only serves to bloat cities and offers partial and temporary solutions to problems of rural poverty. Achieving sustainable livelihoods for the rural poor is thus crucial for balanced and sustainable economic growth.

Partnership between local communities and development planning and programs can be enhanced by building and supporting local institutions that enable broad-based participation. For instance, the conventional top-down process of agricultural technology development and transfer has had some success. But when farmers are actively involved, and technology development and transfer take into account local needs and conditions, the results are far greater and the benefits more broadly shared.

Institutional development is critical. Decentralization and democratic governance facilitate local participation. For small farmers to increase their productivity, they need access to information, services, improved technologies, and markets. Most existing institutions in developing countries fail to meet small-farmer needs. To meet these crucial needs, UNDP supports capacity building in a variety of ways, via innovative approaches and pilot programs such as the Sustainable Agriculture Network and Extension Program, to build technical capacity and networks for field-based nongovernmental organizations (NGOs) and farmers' organizations to link with national research and extension systems.

### Food and environmental sustainability

Broad-based participatory agricultural development that enables environmentally sound growth and innovative approaches to resource management are prerequisites to meeting the overlapping goals of the poverty and environmental agendas. We are now at a juncture where we may have to reinvent our approach to agricultural research and development. Supply-side policies alone may, in fact, be detrimental to both the environment and food security when resource-poor areas and people are marginalized.

An appropriate response will start with a recognition and better documentation of the immense potential for resource cycling and conservation in agriculture for promoting food security and environmental benefits. Can ecosystem-wide impacts of agriculture on biological diversity be mitigated by changes in agricultural practices, technologies, and land use patterns? Will environmentally sound agricultural production practices necessarily mean a sacrifice in economic efficiency, yields, and output? The answers will require work in both the scientific and policy arenas.

Biodiversity is an important aspect of environmental sustainability. By endangering biodiversity, our present habitation and agricultural practices threaten future productivity in some of the most fertile areas of this planet. One solution would be to promote the development of more diverse sets of improved varieties, coupled with major reforms in seed production policies to support localized seed farms and seed marketing systems. These are huge challenges to both crop scientists and policymakers, but not insurmountable ones. They have risen to the challenge before when global food supplies were threatened in the 1970s. Rice breeders and scientists have led the way in the past and can do so again.

Although small farmers are well positioned to adopt labor-intensive agroecological production methods and to produce the high-value produce for which demand is increasing most rapidly, policy frameworks and rural services in many countries can often be biased against the poor and fail to address their real needs. This is particularly true for women farmers, who constitute a disproportionate share of the rural poor and whose incomes contribute most to family well-being, and yet who are denied equal access to development opportunities.

The bulk of UNDP's resources devoted to environmental activities goes to help countries protect and manage the natural resources that are essential to the basic needs of poor people in low-income countries. Four focus areas are sustainable agriculture and food security, water resources and the aquatic environment, renewable energy and energy conservation, and forest management. Other important areas for UNDP include its work on combating desertification and drought in all affected regions of the world.

Building national capacity for an integrated approach to environmental and development objectives is a key goal for UNDP. In a recent program conducted jointly by the public sector and civil society organizations in Zambia, we supported training of about 18,000 women farmers to improve food legume production and storage for environmental sustainability. Legumes are an important source of both food value and income in Zambia. By reaching women with improved technological solutions, a breakthrough in sustainable food security could be achieved.

UNDP also works closely with the Global Environment Facility to incorporate development and long-term food security goals in all environmental programming. In Ethiopia, we demonstrated the potential of farmer-based conservation of their rich plant genetic resources. Genetic diversity is critical for agriculture in marginal lands to survive, improve its productivity, and be environmentally friendly for long-term food security. A similar integration of environment and development has been demonstrated in an integrated coastal zone management program in Belize.

### Food and sustainable livelihoods

The emphasis on environmental sustainability cannot be separated from an emphasis on the livelihoods of people, especially for those who live in ecologically fragile areas.

Environmental and human health concerns often intersect. One example is the development of agricultural systems that promote biological diversity and human nutritional needs. As soon as minimal calorie needs are met, the natural human response is to diversify the diet. Though this can be obvious in regions where demand for grains for human consumption has reached a plateau, a strong case can also be made for agricultural diversification in the newly emerging agricultural growth areas such as sub-Saharan Africa.

Raising agricultural productivity is clearly necessary, as are improvements in agricultural technology on marginal lands, where some 500 million poor people live today. In other regions of the world, where agricultural production and the economy have been on a steady upward trend, the structure of demand is changing. Food needs continue to grow, but food demand will become more complex as incomes rise. Population and income growth will continue to increase demand for food, as will the success of poverty eradication efforts.

In much of Asia, and particularly in most of the rice-producing countries of Southeast Asia, incremental demand will occur primarily in noncereal food groups. Cereals for human consumption will remain important, but diminishing at the margin. Other uses of cereals—such as for livestock feed and industrial and energy uses—are growing rapidly. There is a need for such uses, but agricultural policies need to distinguish where incremental investments would have the greatest benefit to the majority of the people, and particularly for the poor.

The changing structure of demand offers a unique opportunity for investing in areas where land-intensive agriculture is not a feasible option, such as hillsides. High-value, labor-intensive crops, agroforestry, and other biomass-enriching options are well suited to smallholder agriculture characterized by intensive agroecological care. This will require the careful identification of ecological and economic options, market and local institutional support for inputs, outputs, and technical information, and investment for rural income diversification.

UNDP is currently developing a new initiative for dryland regions through the enhancement of natural resources and diversified livelihoods as a means of eradicating poverty and reversing the vicious circle of poverty and environmental degradation.

## Conclusions

Despite recent progress in the production of cereals and in the ability of the world to produce enough food to meet everyone's food needs, the world food situation is beset by crises and by a considerable backlog of hunger and malnutrition. Today, some 840 million people are hungry or face food insecurity. Poverty-related hunger and malnutrition account for 1,700 deaths every hour, mainly children. Thirty percent of the global population lives in households too poor to obtain food for basic needs, and one child in three is underweight by the age of five.

At the World Food Summit, UNDP emphasized that although food production needs to grow, the world already produces enough food to nourish everyone. UNDP also argued for a strong link between food security and poverty reduction. In partnership with FAO and the CGIAR, we aim to ensure that agriculture addresses not only better efficiency in raising output but also efficiency in eliminating poverty and in protecting the environment and natural resource base. This is the challenge of sustainable food security, which we, at UNDP, recognize as one of the greatest challenges facing us today.

## Notes

*Author's address:* United Nations Development Programme. james.gustave.speth@undp.org
*Citation:* Dowling NG, Greenfield SM, Fischer KS, editors. 1998. Sustainability of rice in the global food system. Davis, Calif. (USA): Pacific Basin Study Center, and Manila (Philippines): International Rice Research Institute.

# Part II:
# Food Systems

CHAPTER 3

# Sustaining food security in Asia: economic, social, and political aspects

M. Hossain

Will Asia be able to sustain favorable food balances and further improve food security for low-income households? This paper addresses these issues by assessing the impact of recent socioeconomic developments on the organization of the production of rice, the dominant staple food in Asia. It also analyzes the forces that influence the trends in demand and supply of rice and examines the political factors that could affect the trade-off between pursuing self-sufficiency in domestic production and achieving self-reliance through trade to sustain food security. The paper argues that the rapid increase in rural wages associated with growing economic prosperity, and changes in the tenancy market from sharecropping to fixed-rent tenancy and ownership cultivation, will put an upward pressure on the cost of rice cultivation in middle- and high-income countries and regions that have achieved a high level of productivity. The comparative advantage in rice cultivation will shift from irrigated to rainfed environments. The uncertainty in achieving food security through international trade because of the thin and volatile rice market would encourage middle- and high-income Asian countries to maintain a safe capacity of producing this staple grain through market interventions, although such action is not economically efficient.

Asia has an impressive record of feeding its ever-growing population despite limited land resources. The Green Revolution contributed to a growth in the production of staple grains at nearly 3% per year over the past three decades, keeping pace with population growth and the increase in per capita food consumption brought about by rising incomes and urbanization. A per capita income growth of 2–6% gave many food-deficit countries adequate purchasing power to meet shortages through commercial imports. Yet, despite improvements in food availability, many low-income countries still face food insecurity. Recent World Bank estimates indicate that about 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 changes in Asia's economic situation may affect demand-supply balances for staple grains. Middle- and high-income countries will experience a decline in per capita consumption of rice, the dominant food staple, because of food habit changes associated with rising income and urbanization. Population growth will remain a major force behind the substantial increase in total demand for staple grains for the next 30–50 yr. Also, the demand for maize (corn) and other grains will increase substantially as the consumption of livestock products expands with further income growth. On the supply side, prosperous Asian countries will find it increasingly 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 Trade and Tariffs (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 been almost fully exploited, particularly for the irrigated ecosystem. 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 growth, sustaining food security becomes the major challenge for land-scarce, low-income countries. Affluent Asians could buy rice on the world market by offering higher prices, but the prospect of generating exportable surpluses outside Asia is limited. If the rice supply fails to increase with demand, the price will increase and the market will reallocate scarce supplies from low-income to high-income consumers, a shift that could aggravate poverty in low-income countries. Because poverty alleviation is a major political objective, governments in countries with food surpluses may raise trade barriers to protect their domestic consumers, a reaction that may induce high-income countries to continue their inefficient domestic production of rice.

The question is, Will Asia be able to sustain favorable food balances and further improve food security for low-income households? This paper addresses these issues by assessing the impact of socioeconomic developments on the organization of rice production, analyzing the forces governing demand-supply balances, and examining political factors that could affect the trade-off between pursuing self-sufficiency in domestic production and achieving self-reliance through trade to sustain food security.

## Rice: the dominant food staple and way of life in Asia

### Importance of rice in the economy and culture

In Asia, rice is the principal staple food and the most important source of employment and income for rural people. Asia's hot and humid climate during the long and heavy monsoon season, and the fertile land along the river basins of the major deltas that are regularly flooded, provide the most favorable agroecological environment for rice cultivation. The production of the other staple grain, wheat, raised in a rice-wheat sequence, is limited to the subhumid subtropics, in central China and in the foothills of the Himalayas in South Asia (Huke and Huke 1992). Most Asian nations depend on imports from outside the region for the supply of wheat, whose consumption is low but growing with rapid urbanization and changes in food habits.

Maize is produced in sizable amounts in the sloping uplands of Indonesian outer islands, the Philippines, Thailand, and Vietnam; it rarely competes with rice for land resources. With the fast increase in the demand for livestock products following rapid

**Table 1. Level of food consumption (kg capita$^{-1}$ yr$^{1}$) in selected Asian countries, 1992.**

| Country | Population (million) | Rice (unhusked) | Wheat | Maize | Total cereals | Meat | Fish |
|---|---|---|---|---|---|---|---|
| Philippines | 64 | 133 | 28 | 20 | 181 | 19 | 32 |
| Bangladesh | 113 | 220 | 20 | – | 241 | 3 | 8 |
| India | 884 | 108 | 56 | 10 | 201 | 4 | 4 |
| Myanmar | 44 | 301 | 3 | 2 | 309 | 7 | 15 |
| China | 1,184 | 141 | 83 | 27 | 256 | 30 | 10 |
| Vietnam | 70 | 226 | 4 | 6 | 236 | 15 | 14 |
| Indonesia | 189 | 209 | 14 | 25 | 248 | 8 | 14 |
| Thailand | 57 | 200 | 9 | 1 | 210 | 21 | 25 |
| Malaysia | 19 | 143 | 36 | 2 | 182 | 50 | 24 |
| South Korea | 45 | 157 | 45 | 18 | 225 | 30 | 58 |
| Japan | 124 | 93 | 41 | 21 | 157 | 39 | 75 |

Source: FAO Agrostat database, 1994.

economic growth, the importance of maize as a source of human nutrition dwindles, as it is being increasingly used as livestock feed. Among the cereals, the demand for maize has been increasing at the fastest rate. Table 1 illustrates the overwhelming importance of rice in the Asian diet.

More than 250 million farm households in Asia depend on rice for their livelihood. A typical farm household grows rice along with many other subsistence crops in rice-based farming systems. Farms specializing in the production of a single crop are rarely found, except for plantations where a few perennial crops are grown and in regions where land distribution is highly unequal, such as in the Philippines. More than half of the rice produced is consumed by members of farm households. The marketable surplus varies depending on farm size and rice-growing environment (ecosystem). The surplus for the urban population and the rural landless occurs mostly on irrigated land (nearly 70% of total production) on farms with holdings of more than 2 ha. Rice farms in the upland and rainfed lowland ecosystems are mostly subsistence-oriented. A number of in-depth village studies conducted by IRRI, in collaboration with policy research institutions in national systems (David and Otsuka 1994, David et al 1994, Sudaryanto and Kasryno 1994, Isvilanonda and Wattanutchariya 1994, Hossain et al 1994, Upadhyaya and Thapa 1994, Ramasamy et al 1994, Yifu Lin 1994), estimated the average farm household income at US$1,000 per year, of which 36–57% came from rice cultivation (Table 2). A large portion of the off-farm and nonfarm income came from providing wage labor in rice farming, processing, trade, and transport of agricultural products and inputs.

Because rice plays such an important role in the lives of its producers and consumers, it is little wonder that it occupies such an important position in Asian culture (Huggan 1995). Rice is mentioned in all the scriptures of the ancient civilizations of Asia. Its cultivation was considered as the basis of the social order and occupied a major place in Asia's religions and customs. The Emperor of Japan is the living embodiment of the God of the Ripened Rice Plant. In Balinese (Indonesia) myth, Lord

**Table 2. Average farm household income (US$ $yr^{-1}$) by source in selected Asian countries, 1985-88.**

| Country | Total household income | Sources of income (%) | | |
|---|---|---|---|---|
| | | Rice | Nonrice | Nonfarm |
| Bangladesh | 977 | 38 | 30 | 32 |
| China | 871 | 43 | 30 | 27 |
| India (T. Nadu) | 1,010 | 52 | 36 | 12 |
| Indonesia (Lampung) | 721 | 36 | 44 | 20 |
| Nepal | 1,105 | 43 | 46 | 11 |
| Philippines | 1,072 | 57 | 18 | 25 |
| Thailand | 1,763 | 49 | 20 | 31 |

Source: Compiled from unpublished data collected from household surveys under the collaborative IRRI-NARS project on the Differential Impact of Modern Rice Technology in Favorable and Unfavorable Production Environments. For country case studies on the production, organization, and impact of modern rice technology, see David and Otsuka 1994.

Vishnu created rice and God Indra taught mankind how to raise it. China has a saying that "the most precious things are not jade and pearls, but the five grains," of which rice is the first. Death is symbolized in Taiwan by chopsticks stuck into a mound of rice. Japanese did not use the terms breakfast, lunch, and dinner; the three meals were *asa gohan* (morning rice), *hiru gohan* (afternoon rice), and *ban gohan* (evening rice). In China and Bangladesh, a polite way to greet a visitor is to ask, "Have you eaten your rice today?" Even the names of automobile giants Toyota and Honda have their roots in the rice paddies. The characters for Toyota (originally Toyoda) mean "bountiful rice field" and Honda "main rice field." Debts, taxes, rent, and wage payments to agricultural laborers and rural artisans are still sometimes paid in rice.

## Social organization of production

Rice is cultivated on a small scale in fragmented landholdings. The average size of a farm ranges from 0.43 ha in China to 0.8 to 1.5 ha in most other countries (Table 3). A1-ha farm is often divided into a large number of parcels. Only in Thailand, Myanmar, and northwestern and southern India are farm holdings larger, around 3.5 ha. Farm size varies with population density and land productivity. Regions with fertile land and a developed irrigation infrastructure generally have small farms.

A high incidence of rural-rural migration redistributes people from low to high productive areas. The adjustment of population pressure on land across regions within a country is limited only in countries where land reform laws prohibit the transfer of cultivation and ownership rights, such as in the Philippines and India (Otsuka 1991).

Rice cultivation is highly labor-intensive. In low-income countries with a labor surplus, all farm operations are done manually and use more than 150 d of labor for each ha during a crop season. Transplanting seedlings and controlling weeds alone require 80 d of labor $ha^{-1}$ (Sidhu and Baanante 1984). This work is done mostly by women (Paris 1996). A high degree of seasonality in farm operations, which depend on the rainfall pattern, requires the use of hired labor even on very small farms. Tra-

Table 3. Size and structure of operational holdings and tenancy in selected Asian countries, 1985-88.

| Country | Year of survey | Average farm size (ha) | Distribution of operational holdings (households, %) | | | | Area under tenancy (%) |
|---|---|---|---|---|---|---|---|
| | | | <1.0 ha | 1.0–<3.0 ha | 3.0–4.9 ha | >4.9 ha | |
| Bangladesh | 1987 | 0.87 | 69.8 | 26.5 | 2.8 | 0.9 | 23.3 |
| China | 1988 | 0.43 | 91.9 | 8.1 | – | – | 0.0 |
| India (T. Nadu) | 1987 | 3.54 | 10.1 | 41.6 | 25.0 | 23.3 | 14.1 |
| Indonesia (Lampung) | 1987 | 1.60 | 43.3 | 54.2 | 2.1 | 0.4 | 15.0 |
| Nepal | 1987 | 1.95 | 33.0 | 47.6 | 11.3 | 8.1 | 22.7 |
| Philippines | 1985 | 1.58 | 33.8 | 52.3 | 11.5 | 2.4 | 66.0 |
| Thailand | 1987 | 3.52 | 16.6 | 41.4 | 16.3 | 25.7 | 27.4 |

Source: As in Table 2.

ditionally, farm households used to exchange labor to cope with seasonal demand, but over time this practice has given way to hiring labor on a daily wage or contracting a group of laborers at a piece rate, in some areas in exchange for a share of the harvest (Hayami and Kikuchi 1982, Hossain et al 1994).

Working on others' rice farms is the main source of employment and livelihood for the landless and marginal farmers who constitute one-third to one-half of rural households (except in China and Vietnam, where land is distributed according to the size of the household and number of workers). With growing labor scarcity, increases in wage rates, and the preference of literate young generations for less arduous nonfarm jobs, mechanization to replace labor has been gaining ground, first for threshing and land preparation and then for harvesting and transportation (Pingali 1996).

In many countries, farmers are now adopting the direct-seeding method of crop establishment in place of the traditional transplanting method to save labor and water (Isvilanonda and Wattanutchariya 1994). Another way of saving labor that is becoming increasingly popular is the use of herbicides for weed control. The intensity of labor use and the size of the labor market vary across countries in Asia, depending on the level of economic development, inequality in land distribution, and the extent of mechanization of farm operations (Table 4). An active labor market that promotes seasonal migration of labor, however, tends to equalize wage rates across regions and agroecosystems within a country (David and Otsuka 1994). In countries where land ownership is unequally distributed, the tenancy market redistributes land from large owners to small and marginal landowners; the distribution of operational holdings is thus much less unequal than the distribution of land ownership. About 10–30%of the land is cultivated under various tenancy arrangements, except in the Philippines, where tenants cultivate nearly two-thirds of the land. The sharecropping system is the predominant tenancy arrangement, but it is giving way to fixed-rent and lease contracts with land reform and the spread of modern rice technology (Otsuka 1991, Hossain et al 1994).

**Table 4. Intensity of labor use and importance of the labor market in rice cultivation in selected Asian countries.**

| Country | Reference year | Labor use ($d\ ha^{-1}$) Wet season | Labor use ($d\ ha^{-1}$) Dry season | Hired labor (%) Wet season | Hired labor (%) Dry season | Wage rate (US$ $d^{-1}$) |
|---|---|---|---|---|---|---|
| China | 1991 | 311 | 311 | nil | nil | 0.55 |
| India | | | | | | |
| Punjab | 1987–88 | 101 | n.a.[a] | 69 | n.a. | 1.15 |
| West Bengal | 1984–85 | 148 | n.a. | 58 | n.a. | 0.85 |
| Bangladesh | 1991 | 145 | 170 | 55 | 45 | 1.39 |
| Vietnam | 1992 | 89 | 48 | 38 | 58 | 0.77 |
| Indonesia | 1988 | 135 | 126 | 34 | 65 | n.a. |
| Thailand | 1992–93 | 67 | 105 | 72 | 58 | 2.51 |
| Philippines | 1991 | 60 | 68 | 51 | 67 | 2.28 |
| Japan | 1993 | 58 | – | 1 | – | 91.00 |

[a] n.a. = information not available.
Source: IRRI 1995.

Adjustments in the distribution of production factors through the operation of the land, labor, and tenancy markets have had a positive effect on income distribution, which, to some extent, counterbalanced the unequal distribution of income from the differential adoption of technology across regions and ecosystems (David and Otsuka 1994).

## Economic and political linkages

In Asia, economic development and industrial growth are closely linked to a sustainable supply of rice at low and stable prices. If food prices increase, organized urban labor groups put pressure on employers to raise wages to maintain their living standards. The consequent increase in nominal wage rates reduces industrial profits, hampers capital accumulation, and raises the cost of industrial products. These cost increases affect competitive strength in the world market. The first sign of civil unrest is often traced to rising rice prices, which aggravate the food insecurity of the growing ranks of urban workers and the rural landless, who spend 50–70% of their total income on staple food.

The other factor that encourages government intervention in the rice market is the year-to-year large fluctuations in the domestic production of rice and the resulting instability in prices. In the rainfed areas in South and Southeast Asia, the size of the rice harvest depends more on the vagaries of the monsoon than on farmers' input allocation decisions based on market conditions. Even in regions with a reliable irrigation infrastructure, production is often affected by excessive rains, cloud cover, strong winds and typhoons, cold injury, and insect and disease pressure that also depends on climatic variations. Therefore, prices are often determined by the exogenous change in supply, rather than by changes in supply from variations in input-output prices (see next page). An important political objective in most rice-growing countries is therefore to maintain price stability through domestic procurement, public-sector monopoly in external trade, maintenance of stocks, and the operation of public food-distribution systems for urban consumers and politically sensitive groups (Childs 1990, Hossain 1996c).

Most countries also try to achieve and maintain self-sufficiency in rice production, an objective dictated by the limited availability of foreign exchange to finance major international purchases (particularly for low-income countries) and the experience of unfavorable international deals, in which prices are high in years of deficits but low in years of surpluses. Even high-income East Asian countries with the capacity to procure rice at a much lower cost from the international market follow a policy of maintaining self-sufficiency in domestic production. This policy is followed to guard against the risk of food insecurity during periods of global shortages and political disturbances and to satisfy the farmers' lobby that pressures the government to maintain the balance in incomes between urban workers and rice farmers.

Rice is more important to the economy and people at lower income levels. Therefore, an increase in rice production and productivity not only promotes agricultural development but also contributes to the alleviation of poverty. In countries with a per capita income of US$500 or less, rice accounts for one-fifth to one-third of the gross domestic product, and one-third to one-half of the agricultural value added (Table 5).

**Table 5. Contribution of rice to the national economy in Asia, 1990.**

| Region/ country | Per capita income (US$) | Share of rice in total calorie supply (%) | Share of rice in food grain production (%) | Gross value of rice production (at international prices) as % | |
|---|---|---|---|---|---|
| | | | | Agricultural value added | Gross domestic product |
| East Asia | | | | | |
| China | 370 | 36 | 44 | 37.0 | 10.0 |
| Japan | 25,430 | 24 | 48 | 2.8 | 0.1 |
| Korea, Rep. of | 5,400 | 36 | 59 | 7.2 | 0.6 |
| Southeast Asia | | | | | |
| Indonesia | 570 | 58 | 80 | 37.1 | 8.2 |
| Laos | 200 | 70 | 93 | 46.3 | 32.4 |
| Malaysia | 2,320 | 29 | 86 | 4.1 | 0.8 |
| Myanmar | 533 | 77 | 96 | 48.4 | 24.0 |
| Philippines | 730 | 41 | 67 | 19.4 | 4.3 |
| Thailand | 1,420 | 55 | 95 | 39.3 | 4.7 |
| Vietnam | 220 | 68 | 92 | 43.3 | 21.5 |
| South Asia | | | | | |
| Bangladesh | 210 | 75 | 84 | 62.4 | 23.7 |
| India | 350 | 30 | 43 | 27.7 | 8.6 |
| Nepal | 170 | 42 | 52 | 39.7 | 23.8 |
| Pakistan | 380 | 8 | 12 | 10.4 | 2.7 |
| Sri Lanka | 470 | 42 | 66 | 24.4 | 6.3 |

Source: Hossain and Fischer 1995.

As incomes increase, people diversify their diet with food items (vegetables, fruits, and livestock products) containing more protein and vitamins than rice, and land and labor are shifted (to the extent this is technically feasible) from rice cultivation to the production of agricultural products with stronger markets.

The importance of rice in the national economy dwindles as agriculture's share in national income declines with the faster growth of nonfarm sectors. In Japan, South Korea, and Taiwan, this structural transformation of the economy has already taken place and rice now contributes very little to national income. Yet more than one-fourth of human energy intake still comes from rice. Governments attempt to maintain the rice production infrastructure and to ensure social justice when balancing the interests of farm and nonfarm populations because rice was so important to the economy only a few decades ago.

## Macroeconomic environment and impact on sustainability of rice farming

### Economic growth in Asia

The remarkable progress in the Green Revolution in rice cultivation went hand-in-hand with economic progress in many parts of Asia. Since 1970, for example, the average annual rate of growth in Asia has been a robust 6% $yr^{-1}$, versus 3.2% in South America and 2.4% in Africa (World Bank 1995). Economic growth has also contributed to notable progress in population control, which brought about faster growth in per capita incomes. With an annual rate of growth of about 5% $yr^{-1}$, the per capita income of Asians has doubled every 14 yr since the early 1960s.

The rate of economic progress, however, has been uneven across countries in Asia. Growth has been much faster in East Asia than in Southeast Asia, which in turn has grown faster than South Asia. In Southeast Asia, economies in the Philippines, Myanmar, Cambodia, and Laos grew much slower than those in Thailand, Malaysia, and Indonesia. Agriculture in these countries also experienced an impressive growth, but the faster growth of the nonagricultural sector contributed to Asia's economic prosperity.

In the early 1950s, Asian countries had a similar economic standing, except for Japan. Because of uneven economic growth, however, substantial economic disparity has been created. For example, in the early 1960s, the Philippines had higher levels of income than South Korea, but now the Koreans have incomes that are eight times higher than those of the Filipinos. Also, in the 1960s India had the same level of income as Indonesia, but now (before the recent financial crisis) Indonesians have an income three times higher than that of Indians. As the economy grew, the importance of agriculture declined; vibrant manufacturing and service-sector activities pulled the labor force and population from the rural to urban sector. Higher income levels and greater participation of women in economic activities also led to women giving birth to fewer children and lower population growth.

## Effect on input markets

The growing economic prosperity in Asia is a crucial factor that determines the availability of labor, water, and land for rice cultivation. The competing demand for these inputs from other economic activities affected their relative scarcities and prices, and changed the relative profitability depending on the intensity of use of these inputs in those economic activities.

*Labor and wages.* Economic growth brings about dramatic changes in the structure of employment, the adoption of labor-saving technologies, and increases in labor productivity. With opportunities for more remunerative employment elsewhere, workers move out of low-productivity, low-wage food-production activities. Although the agricultural sector tries to address the problem of scarce labor by adopting labor-saving technologies, it cannot compete with the manufacturing and service sectors, and so productivity gaps continue to grow with economic prosperity. In South Korea, for example, labor productivity in manufacturing increased by 4.3 times from 1966 to 1990, compared with only 1.2 times in the agricultural sector. The total agricultural labor force increased from 4.5 to 6.1 million people between 1966 and 1975, and then started declining in absolute terms, to 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 growth of more than 5% $yr^{-1}$ in per capita incomes, the real wage rate increased by 170% over the 20-year period. In South Asia, where economic growth was moderate, the real wage rate increased by only 50% (World Bank 1995). Table 6 shows the growth in nominal agricultural wage rates over the 1966-91 period for selected Asian countries. In the early 1960s, the difference in wage rates across countries was only marginal. In the slow-growing countries, such as Bangladesh, India, and the Philippines, agricultural wage rates barely increased, but wage rates escalated in Japan and South Korea. The cost of agricultural labor in 1991 was more than 20 times higher in Korea and 65 times higher in Japan than in Bangladesh.

*Availability of water.* Developing water resources has been the key to increasing rice production in virtually all Asian countries, where land is a scarce factor of production. Of all activities for exploiting natural resources, irrigation is by far the most

**Table 6. The relationship between economic prosperity and agricultural wage rate.**

| Country | Per capita income (US$ 1994) | Agricultural wage rate (US$ $d^{-1}$) | |
|---|---|---|---|
| | | 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.

important. Water has generally been regarded as an abundant resource for humid Asia. With the rapidly increasing population, however, water has substituted for scarce land to meet growing food needs. As a result, water is no longer as abundant as it was in many Asian countries. The per capita availability of water resources declined by 40–60% in most Asian countries from 1955 to 1990 (Feder and Keck 1994). By common agreement, countries are defined as water-stressed when the availability is between 1,000 $m^3$ and 1,700 $m^3$. Projections based on constant availability of water and increasing population suggest that China, India, Sri Lanka, Pakistan, and South Korea will approach water stress by the year 2025.

An important issue for Asia is the spatial and seasonal dimension of water availability. Rainfall varies across countries as well as among regions within a country. Most of the Asian region receives rainfall predominantly during a single monsoon lasting 4–6 mo, with almost-dry months for the remainder of the year. The monsoon is often erratic and, in many countries, floods and seasonal water shortages occur concurrently in the same year. If estimates were based on water availability during the dry season, most Asian countries could be classified as water-stressed within the next 30 yr.

As population increases and economic development intensifies, satisfying the needs for drinking water, sanitation, and industrial activities will be accorded a higher priority than agriculture in the allocation of water resources. An economically prosperous Asia now confronts emerging water resource problems that include (1) the stress of meeting human and industrial needs in exploding urban populations, (2) the plateauing of full economic exploitation of irrigation potential in many regions, (3) the expansion of coastal salinity because of the reduced flow of rivers during the dry season, and (4) the rising costs of floods and cyclone damage as economic activity expands into flood-prone and coastal areas. Almost all Asian governments are now faced with tough decisions on long-term plans for the regulation, allocation, and use of water resources.

The scope for further conversion of rainfed land to irrigated land that was the major source of past production growth is also becoming limited (Rosegrant and Svendsen 1992). The cost of irrigation has increased substantially because easy options for irrigation development have already been exploited. Also, environmental concerns—adverse effects of irrigation and flood-control projects on waterlogging, salinity, fish production, and the quality of groundwater—have been growing. Many Asian countries have experienced a drastic decline in investment to develop and maintain large-scale irrigation projects.

*Competing demandfor land.* Economic prosperity and industrial progress lead to rapid urbanization and the concentration of people in a few large cities. Most of the additional increase in population beyond the year 2000 will occur in urban areas. By 2025, an estimated 53% of the people in Asia will live in urban areas compared with 30% in 1990 (UN 1995). This growing urbanization will divert fertile land away from agriculture to meet the demand for housing, factories, and roads. With urbanization and the associated change in food habits, the markets for vegetables, fruits, and livestock products will also 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, the Philippines, Indonesia (Java), and Bangladesh. In China, the area harvested to rice declined from 37 million ha in 1978 to 32 million ha by 1993, and from 3.7 to 3.2 million ha in the same period in the Philippines. This trend indicates that future growth in rice production must occur on less land, with less labor and less water.

## Economic prosperity and competitiveness of rice farming

Despite impressive increases in land productivity, the fast-growing Asian countries have found it difficult to sustain producers' interest in rice farming. This difficulty is not too surprising because many of the gains in productivity and efficiency have been reaped by consumers through declining real rice prices. With the diffusion of modern varieties, producer surpluses have been squeezed by agriculture's treadmill effect (Hayami and Ruttan 1985). Because traditional rice farming is a highly labor-intensive activity, the growing labor scarcity and higher wages have pushed up the cost of rice production and reduced profits and farmers' incomes. It is not only wage laborers who are tempted to move to nonfarm urban occupations; even small-scale rice farmers find it more attractive to leave rice farming and join the industrial labor force. In Japan, Taiwan, and South Korea, the constant outflow of the agricultural labor force has caused a continual decline in the farming population (Morozumi 1993, Park 1993). Aging of the labor force and depopulation in remote areas have continued, making it difficult to sustain rural communities in some areas. Malaysia, Thailand, and China may soon follow in this process.

Rice farmers seek to keep rice farming competitive through (1) improved farm management practices that increase efficiency in the use of nonland inputs and increase total factor productivity, (2) the 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 (3) using the price mechanism to transfer income from relatively well-off rice consumers to rice producers so that the balance between rural and urban incomes can be maintained. In Taiwan, the government developed infrastructure in rural areas to promote the growth of rural nonfarm activities that made possible the simultaneous involvement of rural households in both farm and nonfarm activities. As part-time rice farming increased, the household compensated for the slow growth in farm income with the fast-growing income from nonfarm sources, which partially checked the urge to migrate to urban areas.

In spite of these policies, sustaining farmers' interest in rice cultivation has remained a major challenge to the fast-growing Asian countries. Rice yield has remained stagnant after reaching the Green Revolution frontier. The scope for increasing profitability through the efficient use of inputs has almost been exhausted. As labor accounts for only a fourth of the cost of rice production, substituting capital for labor when the average farm size remains small increases farmers' income only up to

**Table 7. 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$ $t^{-1}$) | 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 and IRRI 1995.

a point. Land prices remain high and increase over time because of extreme population pressure, growing demand for land for housing and industrial purposes, and restrictions on the accumulation of landholdings because of ceilings on ownership in land reform legislation in many countries. In South Korea, rural wage rates and land prices increased at 18% $yr^{-1}$ during 1970-90, when machinery and fertilizer prices increased at 7% $yr^{-1}$ (Park 1993).

As the cost of rice cultivation continued to increase because of the rising opportunity cost of labor and land, governments kept raising rice prices and increasing farm subsidies to maintain a balance between rural and urban household incomes. Protecting the domestic rice industry encourages high-cost domestic 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 United States (Table 7). That difference shifts the comparative advantage of rice production to low-income countries.

Implementation of the GATT Uruguay Round agreements may further dampen incentives for rice production, particularly in middle- and high-income countries (Pingali 1995). Those countries will not be able to compete with low-income countries, where the wage rate and opportunity cost of family labor are low, or with large countries with land surpluses in the developed world (such as Australia, the United States, and Italy) that reap economies of scale because of large farms. If domestic markets are opened for competition, the price of rice will decline substantially, thus providing incentives to consumers to buy imported food staples and forcing farmers to abandon rice cultivation in favor of more lucrative economic activities.

An important way to gain competitive strength in the face of the liberalization of rice trade is to consolidate tiny holdings into large-scale farms as rural households migrate to urban areas and leave their land behind. Precision farming on large-scale holdings, as currently practiced 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 a large reduction in the number of part-time farmers who are now tied up in the supervision of numerous tiny farms. The main constraint to consolidating holdings in Asia, however, is the exorbitant land prices that prohibit the development of an active land market. At present land prices, the rate of return to rice farming from investment in land will be substantially lower than the return to investment in other enterprises.

Because of these forces, middle- and high-income countries will not be able to generate an exportable surplus, even when domestic rice consumption declines with growing economic prosperity. Instead, rice area and production will decline as domestic production is adjusted to demand trends.

## Emerging demand-supply balances

### Determinants of demand

Growth in demand for a staple grain depends on (1) per capita income, (2) population growth, and (3) changes in prices relative to substitute crops. At low levels of income, when meeting energy needs is a serious concern, rice is considered a luxury commodity. With increases in income, people tend to substitute low-cost sources of energy—such as coarse grains, cassava, and sweet potato—for rice. At high levels of income, however, rice becomes an inferior good. As income rises further, consumers adopt a diversified diet and reject rice in favor of high-cost food with more protein and vitamins, such as vegetables, bread, fish, and meat. 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 have already been through these phases and experienced a decline in per capita rice consumption after reaching a high level several decades earlier. Recently, Malaysia and Thailand had the same experience. These high- and middle-income countries—where per capita rice consumption has been declining—account for less than 10% of total Asian rice consumption. The income threshold at which consumers start trading rice for higher quality and more varied foods has not yet been reached in large countries such as India, Bangladesh, the Philippines, and Vietnam. These countries account for more than 40% of total rice consumption and dominate growth in its consumption. Per capita grain consumption in many of these countries is still lower than the peak reached in Korea and Japan during their early phase of development. With increased income and alleviation of poverty, per capita rice consumption may increase further in low-income countries.

To project the consequence of rising economic prosperity in Asia and the change in relative prices for future trends in rice consumption, a study was conducted jointly by the International Food Policy Research Institute (IFPRI) and IRRI. This study estimated parameters of the demand function for the major rice-growing countries of Asia to show the income and price response of demand for rice (Table 8). The estimates indicate that per capita rice consumption will continue to decline with economic growth in high- and middle-income countries such as Japan and South Korea. For other countries, the demand response to income is still positive, although very small, except in countries such as Bangladesh, where poverty is pervasive. If the level of income doubles, per capita rice consumption is expected to increase by 6–11 % in India, Thailand, the Philippines, China, and Indonesia.

**Table 8. The demand response to income and prices for rice, estimates for selected Asian countries.**

| Country | Increase (%) in demand from a 1% increase in income | Increase (%) in demand from a 1% increase in rice prices |
|---|---|---|
| Bangladesh | 0.41 | -0.20 |
| Indonesia | 0.11 | n.a. |
| China | 0.09 | -0.26 |
| Thailand | 0.08 | -0.61 |
| Philippines | 0.08 | -0.93 |
| India | 0.06 | -0.23 |
| South Korea | -0.11 | n.a. |
| Japan | -0.25 | -0.17 |

Source: IRRI/IFPRI (1995) Rice Supply and Demand Project.

The demand response to its own price is also small, which is typical of staple grains. A 10% increase in the price of rice will reduce its consumption 1.7–2.6%. The exceptions are Thailand and the Philippines, where the price response to demand is fairly large, indicating that with an increase in rice prices a large-scale substitution of wheat or other food items for rice will take place. The price response to demand also suggests that a 10% shortage of supply would lead to about a 50% increase in rice prices.

The most important factor exerting upward pressure on rice demand is population growth. With growing economic prosperity, however, population growth has been declining substantially in rice-consuming Asian countries. According to UN projections, annual population growth in developing countries will decline from its present 1.9% to 1.1 % by 2025. Because of 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 past three decades. Ironically, it is in the poverty-stricken regions, where per capita rice consumption is expected to increase, that the population will also grow the fastest (Table 9). In South Asia, for example, the population is projected to increase by 723 million over the next three decades versus 646 million over the previous three decades. Only in East and Southeast Asia is the absolute increase in the number of people going to decline.

Most of the additional population over the next three decades will be located in urban areas. The marketed surplus of rice has to increase substantially to meet the demand from the rising urban population. Global food projections to 2020 made recently by IFPRI (Rosegrant et al 1995) indicate that demand for cereal grains will increase by 72% over the 1990–2020 period, and for rice by nearly 60%, most of this because we will be feeding a larger population. This means that Asian rice production must increase to about 800 million t by 2025, from the present level of about 500 million t, if real rice prices (after adjustment for inflation) are to be maintained at current levels.

**Table 9. Projections of population in major rice-producing and consuming countries in Asia, 1995 to 2025.**

| Country | Population in 1995 (million) | Annual growth rate (% $yr^{-1}$) 1995–2000 | Annual growth rate (% $yr^{-1}$) 2020–2025 | Projected population in 2025 (million) | Increase 1995–2025 (%) |
|---|---|---|---|---|---|
| China | 1,199 | 0.9 | 0.5 | 1,471 | 23 |
| India | 934 | 1.7 | 1.0 | 1,370 | 47 |
| Indonesia | 192 | 1.4 | 0.8 | 265 | 38 |
| Bangladesh | 121 | 1.8 | 1.1 | 182 | 50 |
| Vietnam | 74 | 2.0 | 1.2 | 117 | 58 |
| Thailand | 61 | 1.3 | 0.7 | 81 | 34 |
| Myanmar | 47 | 2.1 | 1.1 | 73 | 56 |
| Japan | 125 | 0.3 | –0.3 | 124 | –1 |
| Philippines | 69 | 2.2 | 1.2 | 115 | 66 |
| South Korea | 45 | 0.8 | 0.3 | 53 | 18 |
| Pakistan | 130 | 2.7 | 1.6 | 243 | 87 |
| Asia (excl. China) | 2,244 | 1.8 | 1.1 | 3,389 | 51 |

Source: World Bank 1995.

## Technological progress in sustaining production growth

The experience of the past 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 trends in production raise concern regarding its sustainability. During 1985-94, rice production grew only 1.6% $yr^{-1}$, versus 3.2% during 1975-85 and 2.9% one decade earlier (Hossain 1996a). Rice production increases are failing to outpace population growth in several countries in Asia (Table 10).

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 modern varieties capable of producing yield that is two to three times higher than that of traditional varieties on lands with reliable irrigation. Past increases in rice yield occurred mainly because of (1) the gradual adoption of modern varieties on existing irrigated land and (2) the expansion of irrigated land through public- and private-sector investment in developing water resources.

The crucial reason behind the slowing of the growth in rice production in recent years is that most farmers have already planted modern varieties on available irrigated land, and the best farmers' yields are already approaching the potential that scientists were able to attain in their experimental fields with up-to-date knowledge. With intensive monoculture of rice on irrigated land, and the heavy use of chemical fertilizers and pesticides, soil and water quality have been deteriorating, and farmers now find it difficult to sustain these high yields (Flinn and De Datta 1984, Cassman and Pingali 1995). In Japan, rice yield has remained stagnant at around 6.5 t $ha^{-1}$ since the late 1960s and in South Korea since the late 1970s. In the humid tropics of South and Southeast Asia, maximum achievable yield is lower than in East Asia by at least

**Table 10. Recent trends in population and rice production in the major rice-growing countries in Asia.**

| Country | Rice harvested area, 1995 (million ha) | Population growth ($\% \ yr^{-1}$) | | Growth in rice production ($\% \ yr^{-1}$) | |
|---|---|---|---|---|---|
| | | 1975-85 | 1985-95 | 1975-85 | 1985-95 |
| China | 31.11 | 1.4 | 1.4 | 3.2 | 0.7 |
| India | 42.30 | 2.2 | 2.0 | 2.4 | 3.1 |
| Indonesia | 11.50 | 2.1 | 1.7 | 5.5 | 2.5 |
| Bangladesh | 9.95 | 2.6 | 2.0 | 2.3 | 1.8 |
| Vietnam | 6.77 | 2.2 | 2.2 | 3.6 | 5.2 |
| Thailand | 9.02 | 2.1 | 1.4 | 3.0 | 0.5 |
| Myanmar | 6.20 | 2.1 | 2.2 | 4.6 | 3.1 |
| Japan | 2.12 | 0.8 | 0.4 | –1.0 | –1.1 |
| Philippines | 3.76 | 2.4 | 2.1 | 3.5 | 1.7 |
| South Korea | 1.06 | 1.5 | 1.0 | 1.8 | –2.2 |
| Asia | 132.84 | 1.9 | 1.8 | 3.2 | 1.7 |
| World | 149.09 | 1.7 | 1.8 | 3.1 | 1.7 |

1 t $ha^{-1}$ because of increased pest pressure and frequent cloudy days with below optimal sunshine (Hossain 1997, Seshu 1988, Seshu and Cady 1984). In humid tropical regions with a good irrigation infrastructure, the maximum attainable yield is about to be reached.

Two technologies in the pipeline may help increase land productivity and input use efficiency, which may aid in further increasing rice supplies. The first is a new type of rice plant, which the media called “super rice.” In 1988, IRRI scientists began to design a new plant type that would increase nutrient efficiency, by reducing unproductive tillers, and increase photosynthesis efficiency through erect and thick leaves (Khush 1995a,b). Field evaluation of breeding lines for this new plant type has begun, and initial observations show that the new plant may have a yield advantage of 20–25% over existing modern varieties. Because of poor grain filling, however, this potential is not being realized. Breeders are now selecting germplasm for improved grain filling and incorporating genes for disease and insect resistance. Agronomists are working to develop an optimal planting method, nitrogen application, and weed control. Further research is also needed to improve grain quality. It may take another 5–10 yr for this technology to reach rice farmers.

The second technology involves developing hybrid rice for tropical regions (Virmani 1994). Hybrid rice has been grown in China since 1976 and has been the main source of the growth in rice production since then. Hybrid rice has an average yield advantage of about 15% over the best inbred varieties. About half of Chinese rice land is now planted to hybrid rice. The Chinese hybrids, however, were found to be unsuitable for tropical regions. IRRI began hybrid rice research in 1978 and has already been successful in breeding lines that show a yield advantage of about 15–20% over modern inbred varieties under tropical conditions. The IRRI materials are now being used in breeding programs in India and Vietnam, and a number of hybrid varieties have already been released to farmers in these countries. The main constraint to the rapid expansion of hybrid rice among small-scale Asian farmers is the development of infrastructure for the production and distribution of seeds, because farmers will need to change seeds every season, an unconventional practice now.

If hybrid rice technology can be combined with the new plant type, rice yield could increase by another 50% when these technologies are fully adopted in all rice lands. Initially, the technologies will appeal to farmers who have already achieved high yields, particularly on land with a reliable irrigation infrastructure.

The greatest potential for increasing rice production lies in rainfed lands, which account for almost half the total rice area. Yield in rainfed lands increased only marginally from 1.5 t $ha^{-1}$ before the Green Revolution to about 2 t $ha^{-1}$ in the early 1990s (Hossain 1996b). Rice scientists have yet to succeed in developing appropriate high-yielding varieties that can withstand prolonged drought, temporary submergence, and other climatic stresses common in rainfed environments (Zeigler and Puckridge 1995). The risk to rice cultivation from unreliable monsoons discourages poor farmers from adopting modern varieties and investing in chemical fertilizers. Increasing yield in the rainfed system will be difficult because scientists have had limited success in developing modern varieties that can withstand climatic and soil-related stresses (Zeigler and Puckridge 1995). With recent advances in molecular biology, research on these issues has been accelerated, but the outcome is uncertain.

### Supply response to prices

If the supply of rice lags behind the increase in demand, the price will increase. The resultant increase in marginal-value products may encourage farmers to use inputs in larger amounts to raise yield and help reduce demand-supply imbalances. To study the magnitude of price response for rice, a number of country studies under the IFPRI-IRRI project used a dynamic supply response model developed by McGuirk and Mundlak (1991). This sequential decision-making model uses a choice-of-technique framework (Rosegrant and Kasryno 1992). Based on the formation of a multiperiod household decision-making process, the model estimates three sets of supply equations using a recursive simultaneous system. The first block of equations determines the allocation of resources to quasi-fixed factors (that cannot be changed in the short run), such as land and irrigation, depending on expected net returns in alternative economic activities. The second block of equations determines the allocation of predetermined land and water resources to crops that compete for these inputs, depending on their relative prices. The third block of equations determines the input supply and yield response of particular crops to input-output prices, given the predetermined levels of quasi-fixed inputs and allocation of area under different crops. The system yields better estimates of supply parameters than the single-equation estimates of area and yield response to price and nonprice variables for specific crops. Table 11 shows the response of rice yield and the supply of modern inputs to rice prices obtained from this dynamic supply-response model.

**Table 11. Input supply and yield response to rice prices: estimates from the dynamic supply response model.**

| Country | Increase (%) in fertilizer from a 1% increase in rice prices | Increase (%) in rice yield from a 1% increase in rice prices |
|---|---|---|
| Bangladesh | 0.20 | 0.06 |
| Thailand | 0.22 | 0.18 |
| Pakistan | 0.30 | 0.04 |
| Vietnam | | |
| Northern region | 0.42 | 0.02 |
| Southern region | 0.17 | 0.09 |
| Indonesia | | |
| Java | 0.43 | 0.05 |
| Java (outer islands) | 0.27 | 0.08 |

Source: IRRI/IFPRI (1995) Rice **Supply** and Demand Project.

**Table 12. Estimates of fertilizer use (NPK $ha^{-1}$) in irrigated and rainfed rice cultivation in selected Asian countries.**

| Country | Irrigated modern variety | Rainfed modern variety | Rainfed traditional variety |
|---|---|---|---|
| China | 368 | – | – |
| Bangladesh | 173 | 109 | 41 |
| Vietnam | 173 | – | 15 |
| India | 172[a] | – | 32[b] |
| Philippines | 114 | 62 | 24 |
| Cambodia | 83 | – | 18 |

[a] Average for Punjab and Tamil Nadu. [b] Average for Bihar and Madhya Pradesh.
Source: IRRI 1995.

The results suggest that the supply response to rice prices is typically small. A 10% increase in price would increase rice yield 0.4–1.8%. The response comes mainly from fertilizer use, which would increase 24% in response to a 10% increase in rice prices. But the output elasticity of fertilizer is small because land, water, and labor are still the dominant inputs in rice production.

What is the potential for increasing supplies through a further increase in the use of chemical fertilizers as the returns from fertilizer increase because of higher rice prices? A number of microstudies carried out in Asia show that when irrigation is reliable, farmers use fertilizers in optimal amounts (David and Otsuka 1994). For the irrigated ecosystem, the variation in fertilizer use among Asian countries is relatively small (Table 12). In most countries in Asia, chemical fertilizers were popular among farmers with large subsidies. In recent years, however, Asian governments have started withdrawing subsidies from this input, which puts an upward pressure on farm-level prices. This trend in prices may reduce fertilizer use and the yield of rice in the irrigated ecosystem, which can only be compensated by an increase in technical efficiency in the use of nutrients.

In rainfed ecosystems, farmers use fertilizer in suboptimal amounts (Hossain and Singh 1995), and rice yield could be increased substantially if they could be induced to move toward optimal levels of application. The main reason behind the low use of fertilizers in this ecosystem is that farmers are not assured of returns from their investment in fertilizer because of the risks of crop failures from floods, temporary submergence, and prolonged droughts. Because most farmers live at near subsistence levels, they are risk-averse and make input allocation decisions on the basis of minimum assured returns (Roumasset 1976). Unless the development of appropriate technologies for unfavorable ecosystems helps stabilize yield, it will be difficult to encourage farmers to use larger amounts of fertilizer in rainfed ecosystems.

## Sustaining food security through trade: political considerations

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 they have better records of food security than the 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 food self-reliance. This requires favorable export growth at the national level to permit countries with deficits to import food from countries with surpluses that can produce it at a lower cost. At the household level, countries with deficits must generate productive employment that provides enough income to acquire the needed food from the market. Most countries in East and Southeast Asia are fortunate in this respect. With growing economic prosperity and poverty alleviation, they are able to meet this condition. In fact, as the cost of rice production increases with rising wage rates, land prices, and scarcity of water, it makes sense—if improving economic efficiency is the primary consideration—to shift 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 the production of staple grains to release resources to 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, we may ask, 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 affluent Asian nations.

An important element of uncertainty in depending on trade to ensure an adequate supply of rice is the thinness of the world market, where only 4% of the rice is traded 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 surpluses 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 destabilize the world market. The volatility of the world market for rice is demonstrated by the surge in prices of high-quality rice from October 1993 to April 1994 in response to a 25% reduction in production in Japan caused by abnormal weather.

With an adequate increase in rice prices, rice area could expand in the humid tropics of Africa and Latin America (Alexandratos 1995). It is estimated that western and southern Africa have 20 million ha of potentially suitable rice land in river valleys, of which only 15% is currently cultivated. In tropical South America, rice cultivation could be extended to an additional 20 million ha. The exploitation of this potential, however, will require a substantial increase in prices and in the capacity of the countries to invest in land reclamation and in developing a 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, FAO 1991). Also, the demand for rice has been growing faster on 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 capacity in rice production. With the alleviation of poverty and the high growth of population, eastern India may need to exploit its excess capacity to meet its growing internal demand. Only Myanmar and Cambodia could generate additional exportable surpluses to partially overcome potential shortages in other Asian countries (Hossain and Oo 1996). The exploitation of this potential, however, would require substantial investment in land reclamation, an expansion of irrigation, technologies for improvement in rice quality, and developing a marketing infrastructure. These countries do not have the economic capacity to make such investments, and they may not be able to mobilize international support because of political instability. Also, the additional exports from Myanmar and Cambodia may not add much to the world rice market because exports from Thailand and Vietnam are likely to decline over the long run. Thailand's comparative advantage in generating an exportable surplus is its favorable land endowment. But this advantage is being gradually eroded by the rapid increase in farm wages and the opportunity cost of family labor, a process that Japan, Taiwan, and South Korea have experienced over the past three decades. The farmers' lobby for raising the domestic prices of rice to reduce the growing disparity between urban and rural incomes is getting stronger. Government intervention in domestic prices will weaken Thailand's comparative edge in the world rice trade. Vietnam has almost exploited its potential for expanding area and production, and may have to reduce exports within the next decade to accommodate growing internal demand.

With 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 distributes scarce supplies in favor of the affluent and, as a result, poor consumers in low-income countries suffer when a staple food is scarce. Rapidly rising food prices will not only accentuate the poverty now prevailing in the low-income countries of Asia, they will also have far-reaching effects on their domestic economies. Because rice is a major component of the food basket, the increase in prices will contribute significantly to inflation and put upward pressure on industrial wages, as the organized labor force bargains to sustain the growth in real incomes. Industrial profits will shrink, and the competitive strength of the economy in labor-intensive manufacturing will erode. When prices soar, the government may intervene in the market to protect the national interest. Imposing a ban on exports of staple food during a scarcity in the domestic market is not a rare event. Stronger nations often use food scarcities as an important weapon to interfere in the domestic politics of weaker nations. Because of the political cost, many Asian countries may maintain a safe capacity of domestic production of staple food despite the additional economic cost of pursuing this policy.

## Conclusions

In humid and subhumid Asia, rice is the principal staple food and most important source of employment and income for rural people. Nearly 250 million households in Asia are engaged in rice farming, with farms varying from 0.43 ha in China to 3.5 ha in Thailand and some parts of India. Nearly a fourth of the rice land is cultivated by tenants, mostly under sharecropping arrangements that are giving way to fixed-rent tenancy with technological progress and growing labor shortages. Rice is more important to the economy and people at lower income levels and is thus an important intervention point for promoting agricultural development and alleviating poverty. In countries with a per capita income below US$500, rice accounts for 20–30% of the gross domestic product, 30–50% of the agricultural value added, and 50–80% of the calories consumed by people. The urban poor and the rural landless, the most vulnerable groups for food security, spend 50–70% of their incomes on rice. Therefore, most Asian governments regard rice as a strategically important commodity, and maintaining stable rice prices is a key political objective. Playing such an important role in the lives of its producers and consumers, rice occupies a major position in Asian culture.

With growing economic prosperity and urbanization, per capita rice consumption has begun to decline in the middle- and high-income Asian countries. Nearly a fourth of Asians are still poor, however, and they have considerable unmet demand for rice. Also, population is still growing at 1.8% yr $^{-1}$ , and Asia may not have a stationary population before the middle of the 21st century. Rice production must increase by another 270 million t over the next three decades to meet the growing demand. It is a daunting challenge to increase rice supplies this much, as land, labor, and water are becoming scarce with increasing competition from the fast-growing nonfarm sectors, and natural resources are already at risk of degradation.

If supply fails to keep pace with the growth in demand, rice prices will increase. Rising prices for this staple food will have an adverse effect on poverty alleviation in low-income countries, which will find it difficult to keep inflation low and maintain competitive strength in labor-intensive manufacturing. This situation may restrict free international trade in rice, with adverse consequences for the access of high-income countries with food deficits and affluent rice consumers to scarce supplies, even though they could afford to obtain rice from the market by offering high prices. The uncertainty in achieving food security through international trade may encourage middle- and high-income countries to maintain a safe capacity to produce this staple grain through market interventions, although such action is not economically efficient.

Asian nations need to formulate a strategy for mutual collaboration to curb population growth, strengthen agricultural research, and develop an irrigation and marketing infrastructure to reduce demand and exploit the untapped potential for increasing supply. International support is also needed to address food security problems in those parts of Asia that still face extensive poverty that threatens the sustainability of the natural resource base.

## References


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

Alexandratos N. 1985. World agriculture towards 2010: an FAO study. John Wiley and Sons. Chichester, England.

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

Cassman K, Pingali PL. 1995. Intensification of irrigated rice systems: learning from the past to meet future challenges. Geojournal 5(3):299-306.

Childs NW. 1990. The world rice market: government intervention and multilateral policy reform. Economic Research Service, USDA, Washington, D.C., USA.

David CC, Cordova VG, Otsuka K. 1994. Technical change, land reform and income distribution in the Philippines. In: David CC, Otsuka K, editors. Modern rice technology and income distribution in Asia. Boulder and London: Lynne Rienner Publishers, Inc. p 51-106.

David CC, Otsuka K, editors. 1994. Modern rice technology and income distribution in Asia. Boulder and London: Lynne Rienner Publishers.

FAO (Food and Agriculture Organization). 1991. A comparison of the cost of producing rice in selected countries. Economic and Social Development Paper 101. Rome.

Feder G, Keck A. 1994. Increasing competition for land and water resources: a global perspective. Paper presented at the workshop on Soil Science Methods in Agricultural Systems: Coping with Increasing Resource Competition in Asia. Chiang Mai, Thailand, 2-4 November 1994.

Flinn JC, De Datta SK. 1984. Trends in irrigated rice yields under intensive cropping at Philippine research stations. Field Crops Res. 9:1-15.

Hayami H, Kikuchi M. 1982. Asian village economy at the crossroads. Tokyo, University of Tokyo Press and Baltimore, Johns Hopkins University Press.

Hayami H, Ruttan VW. 1985. Agricultural development: an international perspective. Revised and extended edition. Baltimore: Johns Hopkins University Press.

Hossain M. 1996a. Asian rice market: a demand-supply analysis. Asian J. Agric. Econ. 2(1):39-52.

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

Hossain M. 1996c. Agricultural policies in Bangladesh: evolution and impact on crop production. In: Abdullah A, Khan AR, editors. State, market and development. Dhaka (Bangladesh): University Press Limited. p 305-340.

Hossain M. 1997. Rice supply and demand in Asia: a socioeconomic and biophysical analysis. In: Teng PS et al, editors. Applications of systems approaches at the farm and regional levels. The Netherlands: Kluwer Academic Publishers. p 263-279.

Hossain M, Fischer KS. 1995. Rice research for food security and sustainable development in Asia: achievements and future challenges. GeoJournal 35(3):286-298.

Hossain M, Singh VP. 1995. Fertilizer use in Asian agriculture: implications for sustaining food security and environment. Paper presented at the Workshop on Plant Nutrition Management, Food Security, Sustainable Agriculture and Poverty Alleviation in Developing Countries, Viterbo, Italy, 16-17 May 1995.

Hossain M, Oo M. 1996. Myanmar rice economy: policies, performance and prospects. J. Agric. Econ. Dev. 23(1&2):110-137.

Hossain M, Quasem MA, Jabbar MA, Akash M. 1994. Production environments, modern variety adoption, and income distribution in Bangladesh. In: David CC, Otsuka K, editors. Modern rice technology and income distribution in Asia. Boulder and London: Lynne Rienner Publishers, Inc. p 221-280.

Huggan R. 1995. Co-evolution of rice and humans. GeoJournal 35(3):262-265.

Huke R, Huke E. 1992. Rice/wheat atlas of South Asia. Los Baños (Philippines): International Rice Research Institute.

IRRI (International Rice Research Institute). 1995. World rice statistics, 1993-94 edition. Los Baños (Philippines): International Rice Research Institute.

Isvilanonda S, Wattanutchariya S. 1994. Modern variety adoption, factor price differential and income distribution in Thailand. In: David CC, Otsuka K, editors. Modern rice technology and income distribution in Asia. Boulder and London: Lynne Rienner Publishers, Inc. p 178-219.

Khush GS. 1995a. Breaking the yield frontier of rice. GeoJournal 35(3):325-328.

Khush GS. 1995b. Modern varieties: their real contribution to food supplies and equity. GeoJournal 35(3):275-284.

McGuirk A, Mundlak Y. 1991. Incentives and constraints in the transformation of Punjab agriculture. Research Report No. 87. Washington, D.C. (USA): International Food Policy Research Institute.

Morozumi K. 1993. Agricultural policy and core farmers of rice farming in Japan. In: Proceedings of the International Seminar on Recent Trends and Future Prospects of Rice Farming in Asia. NACF and FFTC, Seoul, Korea.

Otsuka K. 1991. Determinants and consequences of land reform implementation in the Philippines. J. Develop. Econ. 35(1):339-355.

Paris TR. 1996. The impact of technological change on rural women in Asia. Paper presented at the International Conference on the Impact of Rice Research, 3-5 June, Bangkok, Thailand. Thailand Development Research Institute, Bangkok, Thailand and International Rice Research Institute, Manila, Philippines.

Park JK. 1993. Sustainability of rice farming in Korea. In: Proceedings of the International Seminar on Recent Trends and Future Prospects of Rice Farming in Asia. NACF and FFTC, Seoul, Korea.

Pingali P. 1995. GATT and rice: do we have our research priorities right? In: Fragile lives in fragile ecosystems. Proceedings of the International Rice Research Conference, 13-17 Feb 1995. Manila (Philippines): International Rice Research Institute. p 25-38.

Pingali PL. 1996. Dealing with growing labor scarcity: the adoption and impact of mechanical and chemical technologies in the Asian rice economies. Paper presented at the International Conference on the Impact of Rice Research, 3-5 June, Bangkok, Thailand. Thailand Development Research Institute, Bangkok, Thailand and International Rice Research Institute, Manila, Philippines.

Ramasamy CP, Paramasivam P, Kandaswamy A. 1994. Irrigation quality, modern variety adoption, and income distribution: the case of Tamil Nadu in India. In: David CC, Otsuka K, editors. Modern rice technology and income distribution in Asia. Boulder and London: Lynne Rienner Publishers, Inc. p 323-374.

Rosegrant MW, Agcaoili M, Perez N. 1995. Rice and the global food economy: projections and policy implications of future food balances. Paper presented at the final workshop on the Projections and Policy Implications of Medium- and Long-term Rice Supply and Demand Project, Beijing, 23-26 April 1995. IRRI-IFPRI Collaborative Project.

Rosegrant M, Kasryno F. 1992. Supply response with endogenous technology: food crops in Indonesia. Paper presented at the Planning Workshop on Projections and Policy Implications of Medium- and Long-term Rice Supply and Demand, 25-27 March 1992. Los Baños (Philippines): International Rice Research Institute.

Rosegrant M, Svendsen M. 1992. Irrigation investment and management in Asia: trends, priorities and policy directions. Paper presented at the Planning Workshop on Projections and Policy Implications of Medium- and Long-term Rice Supply and Demand. Los Baños (Philippines): International Rice Research Institute.

Roumasset JA. 1976. Rice and risk: decision making among low-income farmers. Amsterdam: North Holland.

Seshu DV. 1988. Impact of major weather factors on rice production. Paper presented at the workshop on Agrometeorological Information for Planning and Operation in Agriculture, 22-26 August 1988, Calcutta, India.

Seshu DV, Cady FB. 1984. Response of rice to solar radiation and temperature estimated from international yield trials. Crop Sci. 24:649-654.

Sidhu SS, Baanante CA. 1984. Agricultural production, fertilizer use, and equity considerations: results and analysis of farm survey data. Muscle Shoals, Alabama: International Fertilizer Development Center.

Sudaryanto T, Kasryno F. 1994. Modern rice variety adoption and factor market adjustments in Indonesia. In: David CC, Otsuka, K, editors. Modern rice technology and income distribution in Asia. Boulder and London: Lynne Rienner Publishers, Inc. p 107-128.

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

Upadhyaya H, Thapa G. 1994. Modern variety adoption, wage differentials, and income distribution in Nepal. In: David CC, Otsuka K, editors. Modern rice technology and income distribution in Asia. Boulder and London: Lynne Rienner Publishers, Inc. p 281-322.

Virmani S. 1994. Heterosis and hybrid rice breeding. Berlin (Germany): Springer-Verlag.

World Bank. 1995. World population projections, 1994-95 edition. Baltimore, London: The Johns Hopkins University Press.

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

Yifu Lin J. 1994. The nature and impact of hybrid rice in China. In: David CC, Otsuka K, editors. Modern rice technology and income distribution in Asia. Boulder and London: Lynne Rienner Publishers, Inc. p 375-408.

Zeigler RS, Puckridge DW. 1995. Improving sustainable productivity in rice-based rainfed lowland systems of South and Southeast Asia. GeoJoumal 35(3):307-324.

## Notes

*Author 's address:* International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines. m.hossain@cgnet.com

*Citation:* Dowling NG, Greenfield SM, Fischer KS, editors. 1998. Sustainability of rice in the global food system. Davis, Calif. (USA): Pacific Basin Study Center, and Manila (Philippines): International Rice Research Institute.

CHAPTER 4

# A stable landscape? Social and cultural sustainability in Asian rice systems

F. Bray

Agriculture is a human system and agricultural sustainability, however defined, is a goal that has to take into account the social as well as the environmental and technical aspects of farming systems. Social sustainability, environmental sustainability, and sustainable increases in food production are not necessarily compatible. The concept of "landscape" is used in this paper to explore the links and contradictions between these dimensions, and the complex interests that are at stake when transformation in the name of sustainability is proposed. Three examples of wet-rice farming systems in East and Southeast Asia are considered: the Lower Yangzi provinces of China in late imperial times as an example of the long-term social, economic, and environmental equilibrium that progressive intensification and diversification of wet-rice farming can underpin; the contemporary Vietnamese province of Thai Binh as an example of rice monoculture pushed to what appears to be the natural limits of productivity; and the rice-farming sector of Japan, whose acknowledged inefficiencies have not prevented a fierce resistance to reform that unites the nation.

After rain, the typical Asian wet-rice landscape is a patchwork of small fields in shades of emerald green, laced with an intricate web of irrigation channels glittering in the sun. Whether the fields clothe a smooth plain stretching as far as the eye can see or cling precariously in narrow terraces to the flank of a mountain, the emerald green of the growing rice is regularly dotted with darker clumps of trees clustered on the higher, dryland islands of human habitation. Of course, the details of the landscape vary. On the outskirts of Japanese cities, for instance, the proportions between human habitation and farmland are nowadays reversed: farmers in straw hats tend small islands of rice fields lapped by the gray waves of housing developments and shopping malls. But the common features are significant, and stem from a long regional tradition of agricultural adaptation and intensification, whose dynamics differed radically from the historical trajectory of Western cereal farming. The landscape is social no less than topographical. Because of intensive labor requirements, Asian rural populations are dense and farm sizes are minute by North American or West European standards, even in advanced economies like Japan where capital investment is high.

From such rice landscapes the staple food of one-third of the population of the world is produced. But is this sociotechnical system, this crowded landscape with its small fields and small farms, not economically inefficient and wasteful? Must it not be transformed radically or even discarded if the challenges of growing populations and economic modernization are to be met?

Here I would like to suggest that the history of rice in East Asia offers much food for thought, particularly if we are interested in taking the concept of sustainability beyond the primary level of commercial crop production to that of viable rural economies, and even to the level of food symbolism. I present three cases to illustrate the potential of small-scale wet-rice farming as a sustainable basis for a diversified rural economy: from late imperial China, to explain how contemporary rice landscapes evolved; from contemporary Vietnam, where the challenge of overpopulation has been met by technical development designed to combine increased production with participation and equity; and from contemporary Japan, where smallholder rice farming has supported national economic development, and where the current resistance to rice imports shows the immense cultural weight of a highly symbolic food and of the landscape that produces it.

## Social sustainability: local, national, and global concerns

Sustainability in agriculture can be defined at several different levels, often at odds with each other. For instance, a policy that emphasizes the sustainability of world food supplies has as its central goal increasing global food output to match global population growth. Such increases may be achieved in a number of ways, but the checkered record of first- and third-world agricultural development over the past 40 years, with its emphasis on monoculture, capital-intensive inputs, and the displacement of labor, has shown that growth in output is often achieved at the expense of both the sustainable stewardship of the biosphere, an increasingly urgent concern in recent years, and the sustainability of rural communities.

Perhaps because it has played such a visible role as a banner crop of the Green Revolution, and because it is often grown today under industrial or at least highly commercialized conditions, until very recently rice attracted less attention from the ecologically minded as the basis for diversified and sustainable fanning systems than, say, highland Maya crop complexes. But this has changed in the past few years. Concerns about the ecological and economic risks of reduced biodiversity have forged new alliances in which rice farmers' groups collaborate actively with university researchers, government scientists, and international organizations to explore the diversification of local cropping systems in ways that will be stable and sustainable. (For instance, in India, the 1995 conference on "Enhancing and Maintaining Genetic Resources On-farm'' emphasized decentralized and participatory breeding approaches with the goal of combining conservation and development, Sperling and Loevinsohn 1995.) In an interesting populist challenge to the knowledge hierarchies of the modern scientific establishment, sometimes farmers themselves have pioneered new forms of conservational science, eventually attracting the support of academics and government organizations (Frossard 1994).

The main emphasis in this growing movement has been technical, focusing on making better use of rice landraces to reduce the risks inherent in growing a narrow range of imported varieties, to preserve genetic diversity, and, where possible, to reduce environmental damage. Not infrequently, these goals can be achieved without appreciable drops in yields, and the hope is that the next step will be the breeding of hybrid varieties and the development of crop combinations that increase overall outputs. The reduction in capital expenditure on chemicals and new seed is an obvious attraction, particularly to poorer farmers (Salazar 1992). This seems a promising trend toward developing farming technologies that are also economically less divisive. The new research is usually sensitive to the implications of social diversity in local farming systems, recognizing for instance that grain yield may be just one of several factors that affect farmer choice. Moreover, a heartening new interest in multigrain systems is evident, in response to recognition that local hunger may coexist with high overall rice outputs. As Sperling and Loevinsohn (1995) point out, it is often worthwhile "reestablishing a place in agriculture for coarse grains that are crucial for food security in poor households."

East, Southeast, and South Asia, the region in which most of the world's rice is produced, contains more than 70% of the world's small farmers, and has the highest concentration of malnourished and poor people in the world, who depend heavily on rice for their nutrition (Report 1996). Widespread environmental degradation in the region, says the Report, threatens the sustainability of various rice ecosystems. Most small farmers in the region, being poor, are highly vulnerable to risk. Unless positive measures are taken to protect and enhance their livelihood, large numbers will abandon their farms and leave for the cities in search of work that may or may not exist; others (often the women and children) will be left behind to scrape whatever living they can. "Implementing a sustainable agriculture that favors the rural poor is essential, because peasants play a key role in maintaining the food self-sufficiency of most countries, and if their productivity problems are not met, major social consequences are likely to follow" (Altieri 1993).

One of the most urgent tasks for planners is to find ways to strengthen rural economies, and to increase both food output and the numbers of people to whom the local economy can provide a livelihood. In an argument that has found favor with many South Asia specialists, Mellor and Johnston (1984) have suggested that a balanced and dynamic rural economy can be achieved if agricultural development can produce a sizeable group of farmers who spend a good proportion of their income on local nonagricultural goods and services. They argue that the kinds of production stimulated by rising rural incomes are likely to be smaller-scale, less capital-intensive, and more labor-intensive than those typical of urban industries, and so they are likely to contribute to a more equitable distribution of employment. Because this will in turn allow the employed to purchase more food, thus stimulating demand for local crops, this system is likely to be self-sustaining, what Mellor and Johnston call a "virtuous spiral."

Islam (1986, emphasis added) argues that "[an] important precondition for a sustained growth of nonfarm activities capable of generating attractive returns would be a dynamic and egalitarian agricultural sector... the linkage mechanism for mutually reinforcing growth of the two sectors will not work to its fullest extent *unless agricultural growth is sufficiently egalitarian,"* an argument strongly supported by Harriss (1991). It seems that the development of sustainable rural markets, for labor, goods, and services, cannot be separated from questions of equity and improved security for the rural poor.

Like most human and political ecologists, as an anthropologist I would argue that at the local level sustainability, however defined, is unlikely to be achieved unless livelihood and the viability of rural communities are made a priority. Environmental degradation and conservation cannot be tackled effectively at the technical level alone, for they are intimately entangled with social and political factors (Allen 1993b, Thrupp 1993, Le and Rambo 1993). Nor can agriculture be adequately understood as simply a material technology for producing edible calories: it is a human and therefore social, political, and cultural activity.

## The historical legacy of wet-rice technology: the case of China's Lower Yangzi provinces

Here I want to show the historical capacity of Asian wet-rice farming systems to sustain and diversify rural economies. I take as my example China's Lower Yangzi provinces, where what we might call a "rice economy" survived for centuries.

There is a striking contrast between the historical trajectories of Asian rice farming and Western cereal farming. The patterns of technical evolution inherent in the intensification of East and Southeast Asian irrigated rice production do not tend toward economies of scale, whether in the size of holding or in capital investment (Bray 1984, 1986). Briefly, the combination of water, algae, and silt gave premodern wet-rice fields an intrinsically high and stable level of fertility, while the technological requirements of effective irrigation imposed a small scale on individual fields, so that most farmers worked a number of small plots. Although this division of the land has often been considered counterproductive by modern agronomists, it meant that in any one season a farmer could sow several rice varieties, thus reducing the risk of overall crop failure. Chinese farmers had developed several hundred rice varieties by the 14th century (including drought- and flood-tolerant varieties that would mature in 2 mo after transplanting, long-duration varieties with high yields, pest-resistant varieties, and a wide range of colors, textures, and flavors). Unlike modern "miracle rices," traditional varieties grew well even without additional fertilizer and responded well to small quantities of manure, burned stubble, silt from irrigation channels, and lime or industrial by-products such as beancake (Elvin 1973, Bray 1984). (Beancake was the name for the large fibrous discs that were the by-product of crushing soybeans for sauce or bean curd; the extraction of various vegetable oils also produced cakes that were sold as fertilizer. Silkworm droppings and lime were other forms of fertilizer that were commonly purchased. One beancake was apparently enough to fertilize rice seedlings for a whole family farm [Bray 1984].) Not only were individual fields tiny, only a small quantity of land was needed to feed a family. A typical landlord family in the Yangzi delta in the 17th century farmed only 10 mu (0.66 ha) of rice land. (As described in the *Bu nongshu [Supplemented agricultural treatise]* of 1658 by Master Shen and Zhang Liixiang [see Chen and Wang 1983], the family farmed rice for subsistence. The family income came from sericulture, and the amount of land planted with mulberry trees was limited to a similar area primarily by the intensive labor requirements.)

In intensifying rice cultivation, at least until the technical advances of the mid-20th century, such as the laser-leveling of fields, the technological requirements of effective irrigation imposed a small scale not only on individual fields but also on the size of units of management. In the Chinese case, as elsewhere, this by no means ruled out impressive historical increases in yields and output. (For the Lower Yangzi provinces, see Bray 1984. By the 16th century, yields of up to 4 t $ha^{-1}$ of rice or even higher were often recorded.) But these were not achieved through the Western pattern of large-scale rationalized management and heavy capital investment in labor-substituting equipment. Often there were large initial investments of labor in the improvement of irrigation facilities (Bray 1986). But what today's economists would call "divisible" rather than "lumpy" inputs were more important thereafter—improved crop varieties permitting more intensive cropping patterns, the use of manure and cheap commercial fertilizers, and intensive tillage methods that relied heavily on skills but required little in the way of capital equipment (Bray 1986). The lack of scale economies and the importance of the quality of labor in raising yields resulted in a historical evolution of tenurial relations whereby land ownership became concentrated, yet land management did not (Bray 1986). Small production units remained optimal, so access to land was widely available. There was no differentiation into a class of managerial farmers and a class of landless agricultural laborers as in Europe; tenants were selected for their skills, not for their capital assets, and although tenancy increased over time, the conditions of tenure often improved in favor of the tenant as production intensified (Bray 1986).

Rice requires intensive inputs of labor at transplanting and harvesting, which is why rice-farming communities generally had some form of labor exchange and were characteristically clustered into hamlets rather than scattered as individual family farms. In the rice off-season, however, household labor could be spared for other activities, and in many areas of the Lower Yangzi peasant households grew rice almost as a sideline, investing most of their labor in commercial cropping or other forms of household commodity production (Bray 1986). The important point is that rice farming provided a fallback when markets shifted. (For a modern example of how peasants use rice farming to manipulate the articulation of the household and global economy, see Kahn 1980.)

Because rice was sown in separate seedbeds before it was transplanted, it actually occupied the main field for a rather short period (sometimes as little as 2 mo), thus facilitating agricultural diversification and multicropping. In the 17th century, the semitropical regions of the Chinese far south grew two crops of rice a year, with a third catch crop of rape for oil, indigo for dyeing, barley, or sweet potato; the surplus rice was sent downriver to the great port of Canton (Bray 1984). Along the Yangzi, from the 13th century on, it was common to find an alternation of summer rice with winter wheat or barley, or with beans or cotton. Rice could also be grown in rotation with sugarcane, ginger, or other valuable cash crops. In the region around the wealthy cities of Suzhou and Hangzhou, a self-sustaining ecosystem of rice, silk, and fish developed. Mulberry trees were grown on the banks between the rice fields and their leaves were used to feed silkworms, whose droppings were used as powerful fertilizers for the rice. Newly hatched fish were put into the fields soon after the rice was transplanted; they were fed the silkworm molts and they also protected the rice by eating the larvae of insect pests. The men tended the mulberry trees, grew the rice, and caught the fish. The women tended the silkworms and produced the finest silk thread in China, an interesting case because the local people acknowledged that women's work contributed more to the family income than men's. The silk yarn of Huzhou supported a huge local weaving industry in the cities of Suzhou and Hangzhou, as well as the industries of Nanking and Canton (Bray 1997).

Because economies of scale did not operate and little capital was needed to farm well, and although the ownership of wet-rice land tended to be concentrated in the hands of the gentry, the most efficient units of management were small and the countryside remained thickly populated by peasants working as independent or tenant farmers. The nature of the rice technology on which these regional economies pivoted was such as to guarantee access to land for large numbers of people. The diversity of crops and products that the land produced in any one region offered employment to many more. The 15th century saw the Yangzi delta established as a proto-industrial center of cotton production where farmers spent the months between rice crops weaving cloth that was exported all over China. A little further inland were the famous rice and silk regions. In Fujian Province, by the 16th century, combinations of rice with household-based tea or sugar cultivation and processing sustained thriving local economies that traded through Southeast Asia with Europe, and through Manila with the Spanish colonies of the Americas. Economic growth was marked by the proliferation of small market towns that tied villagers into a network of regional, provincial, national, or even international markets. By the 15th century, the volume of the rice trade supplying China's cities was huge, but rural families maintained flexibility and security against market fluctuations by continuing to work their rice lands even as they diversified into other activities.

Many scholars have pointed to China's failure to produce its own technological or industrial revolution and have interpreted the economic changes that did take place as involution or stagnation (e.g., Elvin 1973, with his concept of a "high-level equilibrium trap"), as underdevelopment (Shi 1990), or, at best, as "growth without development” (Huang 1990). For these scholars, the fact that premodern China did not “take off” into exponential economic growth like the early modern West was to be read as a failure. From the point of view of sustainability, however, we might view the history of China’s rice regions as a resounding success.

Rice was first cultivated in the Lower Yangzi some 7,000 years ago, but the rice regions of the south first began to rival the economic importance of the wheat and millet regions of the north during the later part of the Tang dynasty (618-907). By the Song (960-1279), the Chinese made a clear distinction in their agricultural and economic writing between the fruitful and densely populated south and the sparsely inhabited north, where it was hard to wrest a living from the harsh land. It was often pointed out that the north was like a lazy brother living off the generosity of his hardworking and productive sibling. Indeed, between around 1000 and 1700, vast wealth was siphoned off in taxes from the south to maintain the expenses of the northern capital and to support the large standing armies stationed along the northern frontiers.

Numerous factors threatened the environmental and social sustainability of the southern rice economies over the centuries. One was population growth—even such a productive system as I have just described had limits on the number of inhabitants it could support, and over the centuries poor peasants migrated inland to open up rice farms in underpopulated provinces (Rawski 1972, Perdue 1987), or moved to towns in search of work as artisans. Between 1600 and 1800, Chinese statesmen fretted about the vulnerability of the rice regions in the face of population growth, wars, natural disasters, and the siphoning off of their wealth to the north (Will 1994, Bray and Métailié n.d.). But the rice fields themselves did not lose their fertility; indeed, rice yields in a given locality usually increased over time, and Perkins (1969) estimated that food production per capita kept pace with the population increase between about 1400 and 1800 (during which time the population grew from about 60 million to about 300 million). The increase in overall commodity production and trade was also enormous (Liu 1990, Shi 1990), but most manufactures remained rooted in the countryside and in market towns, many commodities such as processed foods and textiles were produced in farming households, and the number of small farmers remained stable. Paul Bairoch (cited in Braudel 1992) calculated that in 1800 living standards in China were still as high as in Europe. If we take the long-term view, as Braudel advises for evaluating the success or failure of an economic and technical system, then we cannot fail to register the system’s flexibility and its long-term technical and political stability, which accommodated steady population growth while sustaining rural prosperity and a flowering of interregional and international commerce. A similar “virtuous spiral” of dynamic prosperity, rooted in economic interdependence among family farms producing rice and other intensive crops, household commodity production, and small urban industrial centers, reemerged in the Lower Yangzi region with the economic reforms of the 1980s (Huang 1990).

## Equity, security, and sustainability—the case of Nguyen Xa village

The village of Nguyen Xa, in Thai Binh Province in the Red River Delta, is an example of the historical legacy of rice intensification carried to extremes. It is almost certainly the most densely populated wet-rice village in the world, and the question is whether the limits of the system can possibly be stretched any further. An interdisciplinary and international team of human ecologists chose Nguyen Xa for their study because it offered an ideal laboratory to examine the nature of human interactions with the environment under conditions of hyperpopulation density that are likely to become *"typical rather than exceptional in much of rural Asia in the next twenty years"* (Le and Rambo 1993, emphasis added. This volume contains 11 chapters that examine the technical, biological, and social sustainability of the Nguyen Xa economy. The contributors are from the Center for Natural Resources Management and Environmental Studies in Hanoi, the Program on Environment of the East-West Center in Hawaii, and agronomic institutions from around Southeast Asia).

Poverty and insecurity are as threatening to the world's resources as wealth, even if the threats take different forms; people desperate to feed their children their next meal cannot reasonably be expected to take a long-term view of resource conservation. Furthermore, it is common to blame much rural destitution on simple population pressure; in the case of rice farming, the term "involution" has often been used. Vietnam is one of the world's poorest and most crowded countries. The case of Nguyen Xa, however, demonstrates that high rural population densities and high labor inputs are not necessarily incompatible with reasonable living standards, security, and a public concern about sustainability. This section examines how Nguyen Xa has met these challenges, highlighting the social factors that helped to consolidate the sustainable rice-based economy that has served Nguyen Xa for 40 years, and discusses the system's potential for further sustainable development and for adapting to the still higher levels of population that are inevitable, at least in the short term.

Farmers were transplanting rice seedlings into paddy fields in the Red River Delta more than 2,000 years ago. The richness of the region's farmlands sustained a succession of Vietnamese dynasties and a steadily increasing population. The Chinese traditionally contrasted the north and south of their country by saying that the north had few people on much land, the south many people on little land (*beifang renxi diduo, nanfang renduo dixi*). "Many people on little land" was not necessarily a negative statement—it expressed an appreciation of the fertility of the southern rice fields and the productivity of rice cultivation methods. But the Chinese recognized that this relationship between land and population could give rise to poverty and insecurity if taken to extremes, in which case *renduo dixi* could be translated, as in the title of Le and Rambo's book, as "too many people, too little land." In the case of the Red River Delta, the extremes had certainly been reached by the 1920s when French agronomists Yves Henry and Pierre Gourou documented the lives of the peasants of Tonkin. The miseries of the rural poor were exacerbated, as these scholars made clear, by the multiple levels of exploitation imposed by the French colonial empire, including the requirement that the land tax be paid in money, not in kind. Gourou and Henry both believed that tenancy and wage labor had been almost unknown in Tonkin before the colonial era (Gourou 1936, Henry 1932). But even if such burdens were alleviated, the French scholars despaired that the land could be made to yield enough to provide adequately for its growing population burden.

Gourou (1936, quoted in Le and Rambo 1993) predicted that population density in the Delta would double by 1984: "A worse situation seems inconceivable; it seems impossible that the Delta, which provides insufficient nourishment for 430 persons per square kilometer today, can meet the needs of a population twice as large." (Henry [1932] put the 1931 population density of Thai Binh Province at 593 persons $km^{-2}$.) By 1991, the population density in Nguyen Xa was 1,497 persons $km^{-2}$, more than three times the stuff of Gourou's nightmare. But the village land produced enough to provide its population with almost 300 kg $yr^{-1}$ of husked rice, well in excess of the minimum nutritional requirement of 200 kg. Furthermore, families that could not meet their needs were provided with extra rice out of the village welfare fund (Le and Rambo 1993).

How was what Gourou would have regarded as a miracle achieved? On the one hand, techniques and technical infrastructure were developed to the maximum to match rice production to local needs; on the other hand, without certain forms of social organization—some modern, some historically rooted—this technical development would not have been possible.

Let us look first at the technical development that underpins Nguyen Xa's miracle. As Le and Rambo point out, Gourou was writing before the development of modern rice varieties, chemical fertilizers, or pesticides. "Since then, the technical basis of agriculture in the Delta has been wholly transformed" (Le and Rambo 1993). Using modern rice varieties, a combination of chemical and organic fertilizers, and intensive labor inputs, the villagers achieve extraordinarily high yields: in 1990, the average annual production was 9.76 t $ha^{-1}$ of rice, and 1 ha of first-class rice land might produce 15.5 t of rice, 14 t of potatoes, 6.5 t of rice straw for fuel, and 5.6 t of potato vines for pig feed. In terms of human labor inputs, however, there has been no transformation, but rather an intensification as pasture areas shrink to make way for extra rice fields. On average, families devote 233 labor days $ha^{-1}$ $crop^{-1}$ to rice, almost all of which is manual labor; all too often men and women take the place of draft animals pulling the plow or the harrow (Le and Rambo 1993).

The socialist state that came to power after independence in 1954 laid the base for this productive system, effecting a political and physical transformation of the rural landscape. Social investment and local collectivization established the basis of the new economic and productive order. First, large-scale water control projects eliminated the devastating floods that used to ravage the Delta. (Vietnamese annals record 74 great floods of the Red River between 997 and 1775. The first dike was constructed in the late 9th century, a web of inland and coastal dikes was built up over the centuries, and flood control was a constant concern of successive dynasties. The post-independence state was able to mobilize labor and design water control facilities with unprecedented efficiency; nevertheless, the threat of flooding remains and the modern government still invests in a Central Committee for Flood and Typhoon Prevention and Dike Protection [Le and Rambo 1993].)

> "Decisions about optimum land use (e.g., alignment of irrigation canals) could now be made on purely technological grounds without concern for the impact of such projects on a multitude of individual plots. Labor could be mobilized in vast quantities to construct dikes, canals, roads, and other productive infrastructure. A network of agricultural research and extension services was established to provide plant breeding and pest control services to the Cooperatives. At the same time, nationwide campaigns were launched to eradicate illiteracy and inculcate scientific ways of thought" (Le and Rambo 1993).

In Nguyen Xa, a water control system was constructed that has made double cropping possible on most land and provided almost total security from floods, while local irrigation canals and pumping facilities assure some supply of water even in droughts. State agricultural stations work closely with local farmers' organizations to supply fertilizers, disseminate new varieties and new skills, and market rice surpluses,

Adopting such technical packages does not always improve the lives of poor farmers; indeed, in many local applications of the Green Revolution, it has seriously undermined their livelihoods. In the case of Nguyen Xa, however, the socialist policies of the post-independence government meshed with the traditional local networks typical of wet-rice communities to facilitate an equitable spread of benefits. First of all, land ownership and water rights were vested in the Cooperative (run by village members) and land was allocated to households on a yearly, rotating basis. To meet the requirements of peak periods in rice farming, the Cooperative built on traditional forms of organized labor exchange but expanded and rationalized them. In the wake of the economic reforms of 1986, which restored economic independence to individual households, the traditional forms have revived the Cooperative system and thus "maintained the base for what is today still a complex and effective social system" (Le and Rambo 1993). The Cooperative was also responsible for providing new crop varieties and technical information, for organizing water control at the village level (hamlet organizations ran the local units), and for allocating the use of the village buffalo, who were communally owned and pastured.

The collective system attempted to promote security and equity for all its members. Taxes on land, paid in rice, were and still are the primary revenue source for the village government. A large part of the heavy tax-in-kind paid on rice land goes to providing local services—schools, clinics, and a rice fund that helps families with poor crops during emergencies; it also finances festivities, including the water-puppet performances for which the district is famous (Le and Rambo 1993). As a result, the population of Nguyen Xa is literate, healthy, decently clothed, and culturally sustained, but the people have to work extremely hard for these privileges.

If ever there was a rice economy, Nguyen Xa is it. In 1991, a population of about 6,500 lived on a total surface area of 430 ha, of which 305 ha were cropland. This means that each person has only 490 $m^2$ of cropland to support him or her; however, since much of the land is double or even triple cropped, the nutritional density is 9 persons $ha^{-1}$ of cropped surface. To feed its population, the villagers use every inch of land that can be irrigated for multicropped rice; even the canal dikes and the bunds between fields have been whittled down to the limits of safety to gain a few precious extra rows of rice. We are dealing here with a totally human-shaped, or rice-shaped, environment in which there are no wild plants except for the weeds in the rice fields, and no wild fauna except for water snails, houseflies, and the occasional sparrow that strays in and becomes an immediate target for small boys with slingshots. (The local frog population diminished almost to extinction after prices rose in 1990, following the resumption of relations with China [Le and Rambo 1993] .) In any season, villagers are likely to plant only four different varieties of tested high-yielding rice on most of their land, though they also reserve about one-fifth of the land for trying out new varieties provided by the local agricultural extension offices, and they still grow small areas of traditional glutinous rice, which not only fetches higher prices but also helps them limit pests.

In 1986, the communes were disbanded under a new system, *doi moi,* whereby family units operate independently. Cropland, which before 1988 was redistributed every year, is now theoretically redistributed every 10 yr, though in practice it appears that usufruct rights are permanent and hereditary (Le and Rambo 1993). As in China under the New Economic Policies, this has led to a flourishing of the rural economy as families work hard to improve their incomes. But in Vietnam, as in China, the welcome improvements in living standards have to be measured not only against the social dislocations that incipient economic differentiation between families and between regions may engender, but also against the ecological dangers involved in commercialization and competition, such as higher fertilizer and pesticide use and the neglect of the communal infrastructure resources that made this prosperity possible in the first place. Moreover, in Vietnam as in China, strict birth control policies are unlikely to stabilize the population for some time to come, because life expectancy has increased significantly. In rural Nguyen Xa, young couples find it hard to get land for a house plot, there is no room for the school to expand, and sweet potatoes are grown between the graves in the military cemetery. Can the system be expanded further? Can it even be maintained at these levels?

Vietnam's attempts to generate internal industrialization in the 1970s and 1980s failed, and in 1991 both internal and international opportunities for employment outside the village were declining and there was little hope for reducing pressure on land, particularly because villagers were extremely reluctant to leave their familiar community. But this might change as international capital moves into Vietnam in search of cheap and well-educated labor. The farmers were quite aware of the perils that their specialized environment presented, but they had always been well served by the state agricultural services and they continued to have faith that science would solve their problems as they arose. But ecologists fear that such a land-intensive system might collapse, as it has elsewhere. Even if the use of organic fertilizers increases and new super breeds as planned by IRRI are developed, the rate of transformation of energy into food or economically useful products in Nguyen Xa is already extremely high compared with other agroecosystems. Nguyen Xa rice monoculture converts approximately one-half of its energy inputs into humanly edible calories versus one-third for maize monoculture in the United States and rice monoculture in Japan. Ecologists doubt whether there is any potential for raising yields further (Le and Rambo 1993).

Even maintaining the rice system at a stable level will depend on carefully managed fallows, crop rotations, and inputs of organic manure to preserve the soil, all of which have become more difficult with the abandoning of communal management. Take the example of *Azolla.* The cultivation of *Azolla,* an algae that grows on the surface of paddies, has declined considerably since the reforms. It used to be widely cultivated during the spring crop: 1 kg of plants put into a paddy would produce 300 kg of nitrogen-rich green manure. The Cooperative allocated land for reproducing *Azolla* over the winter, but now individual households do not set aside land for this purpose and the amount of "seed" available is insufficient to supply all fields. Farmers also say that "since irrigation water flowing through their fields carries away much of their *Azolla* to benefit other farmers downstream, it is not worth the time and effort to maintain it" (Le and Rambo 1993). In addition, the yields of modern varieties tend to degrade after a few years and they become susceptible to pests or disease, so they must be replaced by new varieties; therefore, close collaboration between villagers and state agricultural research stations is necessary. But the reform cutbacks have affected the national rice breeding program and agricultural extension system, and this is especially worrisome for the future of rice production.

Despite the tiny cash flows and large proportion of rice consumed within the household, the villagers of Nguyen Xa are not subsistence farmers operating within a closed system. They are politically integrated into the Vietnamese state; their dependence on rice prices, chemical fertilizers, modern varieties, and markets for the commodities they produce integrates them into truly global networks. The main village workshop, a mat-weaving cooperative, had to close when the Soviet Union, its chief customer, collapsed. The rice varieties the farmers depend on are bred by stations in the Philippines or Indonesia. Most of the villagers' technical and economic choices depend on the price of rice, which is determined by world commodity markets. They try to balance sustainability concerns against the need for food and income, regularly adopting new varieties and rotating chemical fertilizers, but all their choices are dictated by factors beyond their control. For instance, chemical fertilizer prices increased steeply between 1989 and 1991, when Russia ceased economic assistance to Vietnam.

Families now consume most of the rice they produce and, after paying taxes, have little surplus. If rice is short, they sell a pig to buy food. The poorest families usually depend most heavily on rice farming; slightly better-off families may also buy and sell scrap or work in the off-season in the garbage dumps of Hanoi. Some families have enough capital to invest in a household manufacture, such as bean curd or noodles, or in a stock of cheap goods, such as candy or children's clothes for local retail. Finally, the families with regular, stable off-farm income are those that have been able to invest in a rice mill or a truck. Because rice farming is taxed and alternative economic activities are not, there is potential here for disruptive economic differentiation (Le and Rambo 1993).

Because of the extreme scarcity of land in Nguyen Xa, even minor variations in quantity and quality affect a household's ability to produce sufficient food. Although elaborate rules and procedures have evolved to ensure that land allocation among households is relatively equitable, competition is keen, if covert. But distribution remains under official control, and is still highly equitable. People are loyal to the Cooperative, which has survived the reforms in part because of the services it still offers (including irrigation management and the dissemination of technical information and new varieties). But the moral basis of attachment to the Cooperative should not be underestimated, because it comes from a feeling of solidarity and commitment to community rooted in the shared struggle to build a modern Vietnam (Le and Rambo 1993).

In Nguyen Xa, incipient economic differentiation was already perceptible in 1991 as a result of the reforms, but the disadvantaged were still few in number and the Cooperative welfare system still had enough funds to meet basic needs. Maintaining mechanisms of solidarity remained an important objective for many villagers. For instance, the persistence of labor-exchange groups within the new, more individualistic economic order permitted the hyperintensive multicropping system to operate without recourse to labor-saving—but energy-intensive—machines. If the villagers' commitment to such forms of solidarity is disrupted, environmentally less desirable farming practices will inevitably succeed them. But villagers continue to exchange labor and are not receptive to rationalizing rice production by introducing private ownership of paddy land and consolidating plots (Le and Rambo 1993), the classic mechanism of economic polarization in so many Green Revolution scenarios.

There still appears to be a solid socio-technical base on which the current virtuous spiral could be further developed to turn disadvantages into advantages. The main hope seems to be to overcome the dependency on rice.

Nguyen Xa has plenty of surplus labor (74% of employed labor is devoted to agriculture and only 16.5% to other forms of material production) but no credit institutions (Le and Rambo 1993), and the emphasis on rice monoculture produces few local materials that can be processed into salable commodities. All land that can be used is used for paddy, leaving little space for vegetable gardens or pasture. Farmers say they cannot spare money to raise pigs, for which there is a good market in nearby towns, and which would also increase the available quantities of organic manure and reduce the dependency on purchased chemical fertilizers. We might surmise that low-cost credit facilities would bring substantial returns in diversifying production and increasing cash incomes, and a progressive tax on nonfarm income would help spread the benefits of this diversification among the community. (Oxfam has apparently had considerable success in Vietnam with low-credit loans for small-scale agriculture and micro-enterprise development [*Update Vietnam,* Oxfam America newsletter, May 19961].) If families had more cash, they could also buy extra rice on the market, which should not be impossible in a nation that is now the world's third-largest rice exporter. This would reduce the pressure to maximize rice production and allow diversification of land use in Nguyen Xa, such as expanding gardens, extending pastures to raise more livestock (for manure, for meat, and for sale to the towns), growing a wider variety of crop plants, and planting trees for fuel, all of which would help increase biodiversity and benefit local soils.

Can Nguyen Xa survive? Le and Rambo (1993) convey the complex interdependence of social and biological sustainability, and argue that technical measures are only likely to be effective within an overall strategy of equitable and socially sustainable development. Although Nguyen Xa is now undergoing a transition from which either a virtuous spiral or a vicious circle may emerge, its achievements over the past 40 yr are undeniable, and implications for addressing food and poverty issues elsewhere in Asia should not be ignored.

## Japan: rice and the sustainability of culture

In the late 1980s, United States rice farmers began asking their Trade Representative to pressure Japan to open up its markets to imports of foreign rice, particularly California rice, which consists of varieties originally imported from Japan. Rice does play an ever-diminishing role in the Japanese diet as Western-style foods such as bread become popular. Nevertheless, farmers and the general public formed a united front against rice imports.

After several years of fierce opposition, at the final round of the Uruguay GATT negotiations in late 1993, Japan was obliged to open its doors, if only a crack, to rice imports. In March 1994, the Japanese government allowed foreign producers (from Australia, India, Thailand, and the United States) to exhibit rice for the first time at the annual food show in Tokyo. Japanese consumers believed unanimously that foreign rice could not match Japanese rice for texture and flavor and said that they were happy to pay high prices for high-quality Japanese rice. In questionnaires, more than 70% of the Japanese said that they preferred domestic rice even at higher prices. But in blind taste tests, 60% could not tell the difference between Japanese and foreign japonica (*Guardian Weekly,* 13 March 1994). I visited Japan in October 1994, just after the rice harvest. In the basements of large city department stores, which specialize in luxury foods, rice from up to a dozen well-known rice-producing areas was on sale at high prices. The only other products with comparable ranges of variety and origin were tea, coffee, and wine. The big news announcing that "the new rice is here!" reminded me of "le Beaujolais nouveau est arrivé!" campaigns (now a yearly event in Tokyo as well as in Paris and London). Meanwhile, in less elegant streets, the cheap food stalls with food for carry-out were festooned with banners proclaiming that their dishes all used "100% Japanese rice."

In direct economic terms, as Ohnuki-Tierney emphasizes in her study of *Rice as Self* in Japan, the campaign made little sense on either side, as the amounts of rice at stake were insignificant compared with the other Japanese imports of food crops from the United States. U.S. rice farmers were asking for an eventual quota of 10% of the Japanese market, at a time when Japan already purchased 77% of its maize, 88% of its soybeans, and 59% of its wheat from the United States (figures published in 1987 by Zenchû, the Japanese farmers' union; Ohnuki-Tierney 1993). The Japanese are normally enthusiastic consumers of foreign goods varying from luxury cars to Thai shrimp and French wine. Furthermore, many urban Japanese deeply resent the large subsidies that farmers receive from the government, as well as the fortunes to be made from selling farmland for building. Why, then, did farmers and townspeople unite in support of native rice?

To understand why home-grown rice and the paddy landscapes where it grows command such loyalty in a country that has long since left behind its agrarian economy, we need to examine the traditions that Japan has created for itself in the process of modernization, and the place of rice as a food and landscape in the identity of contemporary Japanese. The following statement from the Zenchû report cited earlier is typical of what we might call the "discourse of rice," an important element in the contemporary theory of Japaneseness (*nihonjinron*):

> In Japanese agriculture, rice carries incalculable weight compared with other crops. It is no exaggeration whatsoever to say that the maintenance of complete rice self-sufficiency is the sole guarantee to agriculture and farming households in Japan. Rice farming in Japan, with a history of 2,300 years behind it, has greatly influenced all areas of national life, including social order, religious worship, festivals, food, clothing and housing, thus molding the prototype of Japanese culture. (*Zenchû Farm News 5,* Jan 1987, trans. Ohnuki-Tierney 1993.)

Historically, early modern Japan experienced the almost exact technical parallel of rice-based rural economic diversification and growth that occurred in late imperial China, though in the Japanese case it has not been interpreted as involution or stagnation (Smith 1959, 1988, Francks 1983). Many scholars have pointed to the crucial role of the agricultural surplus in generating capital for the industrialization of Japan in the 19th century (Hayami and Tsubouchi 1989, Byres 1991).

Partly as a result of the high taxes levied to finance modernization, conditions for tenant farmers became increasingly exploitative during the late 19th century and remained so until the land reforms imposed by the Americans during the post-World War II period of occupation, despite official policies to alleviate rural poverty (Goto and Imamura 1993). Poor farmers were cajoled and spurred to further patriotic efforts by assurances of their essential contribution to nation building and to the support of the army and the new Japanese colonies. The official ideology of agrarian fundamentalism assured poor peasants that they contributed spiritually as well as materially to the imperial order, not only growing the pure rice that gave strength to Japanese soldiers, but cultivating the quintessentially Japanese landscape of paddy fields. The representation of Japan as a nation tied to its legendary roots by the labors of simple, thrifty, and patriotic rice farmers served Japanese nationalist parties well from the 1870s to the end of World War II, and it still has popular appeal today. (See Bray 1986 for a brief account of the literature on agrarian fundamentalism in Japan.)

As in the Yangzi provinces of China, the rural Japanese social structure was shaped by the specificities of intensive wet-rice farming (Kada and Goto 1993). The narrow tracts of arable land between the mountains were densely populated, farming relied on labor-intensive methods to produce high yields, and farms were small although land ownership was concentrated in relatively few hands. During the early period of modernization, rural crowding allowed for extreme exploitation of the peasantry, but since 1945 the level of rural population has favored farmers. The proportion of the Japanese electorate registered as rural voters is extremely high for an industrial economy and the LDP, the ruling party in Japan from the end of World War II, has been kept in almost unbroken power largely thanks to a loyal rural vote.

With the introduction of universal suffrage in 1945, the new Japanese government distributed "land to the tiller." To eradicate the power base of the former militarist elite, it enacted land reforms that did away with tenancy and set stringent limits on the purchase of land, thus institutionalizing the small but independent family rice farm. The experience of near starvation during World War II, together with obligations to the new class of voters, prompted a series of agricultural policies and subsidies designed to guarantee national self-sufficiency in rice while eliminating rural poverty (Goto and Imamura 1993). The flexibility of the smallholder rice farm supplied the framework for the successful long-term balancing and integration of rural and urban development that has made today's Japanese population the wealthiest in the world.

In the name of rice self-sufficiency, the government has paid rice farmers heavy subsidies and price support since the 1950s, transforming Japanese rice farming into one of the most capital-intensive and energy-dependent agricultural systems in the world. From the environmental perspective, the strategy of increasing rural incomes by raising rice prices has backfired. Until the 1960s, Japanese rice farmers used moderate amounts of chemical fertilizers, motor pumps for irrigation, and simple threshing machines. Since the 1960s, small-scale tractors, transplanters, and harvesters have been developed specially for small-scale rice production, allowing farming families to take up the off-farm jobs generated by rural or small-town industrialization. Most of Japan's 4 million farming households now work their farms part-time and earn a combined average income higher than that of urban families (Ohnuki-Tierney 1993, Goto and Imamura 1993). They usually own a full range of expensive machinery even though the average farm size is 1.2 ha. (This average includes the large stock and dry cereal farms of the northern island of Hokkaido; the typical rice farm is even smaller, more than half being under 0.5 ha in size. Many farmers are quite heavily in debt because of their investments in machinery and other operational costs; their off-farm incomes thus help subsidize the costs of farming. Goto and Imamura 1993.)

It cannot be argued, even in Japan, that this form of production is economically sound. It costs 15 times as much to produce 1 kg of rice in Japan as in Thailand, and 11 times as much as in the United States, so price was one argument used against Japan during the importation debate by Americans and other free-market advocates. But the Japanese public is not concerned about price but about quality. Rice prices are a very small part of household expenditure on food for most Japanese today. Standards of living have risen and Japanese families now consume only small amounts of rice compared with other foods (although rice is still "real" food, the only food that satisfies hunger), and most middle-class families are willing to pay the highest prices for the best varieties of rice, of which there is never a sufficient supply, even though Japan produces a rice surplus (Morishima et al 1993). The public snaps up expensive gift packs of new-season rice of fine varieties to give to family and friends (Ohnuki-Tierney 1993).

Nor can it be argued, even in Japan, that Japanese rice production is environmentally sound, at least as far as chemical use is concerned, and Japan has many powerful consumer groups that one might have expected to take up this issue. As long ago as 1977, Japanese economist Taketoshi Udagawa calculated that energy inputs amounted to three times the food energy of the rice itself. The average fertilizer use is 1,110 kg $ha^{-1}$ for rice (it is 160 kg in the United States and 48 kg in Thailand; Bray 1994). The irrigation channels and soil are saturated with chemicals. No fish or frogs swim in the paddies any more, and most country children have never seen a firefly (Moore 1990). Ironically, one of the arguments used against California rice by the Farmers' Union, Zenchû, was that large amounts of chemicals were used to grow it, whereas Japanese rice was chemical-free! Japanese consumer groups knew better, and Zenchû was obliged to withdraw this argument. But although a survey in November 1988 by the Japanese Economic Daily (*Nihon keizai shimbun*) indicated that 46% of consumers favored reforming rice production to increase organic cultivation and the selection of varieties, recognizing that native production methods are heavily chemical-dependent does not prevent the majority of Japanese from seeing their home-grown rice as essentially pure and strengthening, while foreign rices are impure (Ohnuki-Tierney 1993).

Furthermore, Japanese rice farming also purifies and maintains the landscape. At the height of the debate on rice imports, a journalist declared that "American rice would not clear the air, nor would it adorn the scenery with beautiful green" (Ohnuki-Tierney 1993). Numerous Japanese scientists and engineers have argued that rice paddies are essential to prevent flooding and soil erosion and to maintain water tables (e.g., Ozawa 1993). Smil (this volume, Chapter 19) refers to one study carried out for the Ministry of Agriculture, Foresty and Fisheries that estimated that in 1990 figures "the land and environmental preservation function of rice paddies" was worth ¥12 trillion a year, or three times the total value of the rice produced. To materialist arguments, economists and scientists join impassioned aesthetic and cultural pleas (Tweeten et al 1993): if the rice paddies go, the beautiful traditional Japanese landscape, the traditional Japanese sense of community, a whole worldview, will disappear. This concern is widely shared and, in a highly urbanized society like modern Japan, it is not surprising to find that enormous value is placed on the preservation of the traditional countryside and its rural population. (See Williams 1973 for the argument that it is the growth of cities that makes necessary the notion of the "countryside." On the importance of rural imagery in the construction of tradition in Japan, see Berque 1990, Goto 1993, and Robertson 1991 .)

In sum, when a modern Japanese family and its members sit around the supper table eating their bowls of Japanese-grown rice, they are not simply indulging a gastronomic preference for short-grained and slightly sticky japonica rice over long-grained indica rice from Thailand. They are eating and absorbing a tradition, in the sense of an invented and reinvented past. The modern adaptation of peasant rice farming provides the urban Japanese with a sense of belonging, an emotional and aesthetic refuge from rapid modernization and internationalization. Japanese rice is consumed not only as a food that evokes a national essence; it also represents a harmonious rural landscape, a weekend escape from the unnatural conditions of life in the modern city. While the television beside the dining table emits a stream of images of the here and now, of an urbanized, capitalist, and thoroughly internationalized Japan, each mouthful of rice offers communion with eternal and untainted Japanese values, with a rural world of simplicity and purity, inhabited by peasants tending tiny green farms in harmony with nature and ruled over by the emperor, descendant of the Sun Goddess, who plants and harvests rice himself each year in a special sacred plot. Simple peasant rice farmers are a dying breed in contemporary Japan, but the small rice farm lives on as a powerful symbol, and Japanese rice is the food that makes one a pure Japanese. Although Japanese rice farming may fall far short of the general goal of sustainability in terms of energy use and economic efficiency, in terms of political, cultural, and aesthetic sustainability, it must be deemed a resounding success.

## Conclusions

The case of the Lower Yangzi in premodern times outlines a typical socio-technical trajectory of wet-rice intensification, and helps us put into context the rice economies of Asia today and their potential for sustainable development. The historical pattern of evolution in Asian rice farming, like the contemporary cases of Vietnam and Japan, suggests that the specificities of rice-farming systems make them potentially solid bases for sustainable, high-density rural economies, with the proviso that sustainability is multidimensional and cannot be reduced to technical features alone, any more than the economy can be reduced to mere figures. As Friedmann (1993) reminds us, the economy is a human artifact, and agriculture is a human activity designed for human ends. Community, equity, and a sense of identity and self-respect are not luxuries but human necessities; they are essential underpinnings of sustainable development in the modern world.

With the consolidation of the disciplines of human and political ecology, the social and cultural dimensions of sustainability are receiving more serious consideration. It is now widely acknowledged that environmental degradation and conservation cannot be effectively tackled at the technical level alone. Landscape and the meaning of the food on our table are not mere incidentals in the sustainability debate. The Vietnamese case illustrates the challenge of not just producing enough food but of also providing a decent and secure living, the challenge of rural poverty that still affects most Asian nations. The Japanese case requires us to consider whether we need a countryside, a food, and a landscape to reflect on the implications of abandoning indigenous farming in the name of economic rationality.

There are those who doubt that sustainability of any kind is compatible with capitalist competition (see O'Connor 1993). Certainly in both the Vietnamese and Japanese cases it seems to be the pressure of global markets that offers the most serious threat to the survival of local economies.

One of the most potent and destructive weapons in the free-traders' armory is the specter of world starvation. In November 1996, the U.S. Secretary of Agriculture, Dan Glickman, told the World Food Summit: "Our farmers plant for the world, and want to compete in a global market free of trade barriers. They need a level playing field, and the world needs our exports to eradicate hunger." Kevin Watkins reports that cheap U.S. maize imports to the Philippines have contributed to disastrous impoverishment and malnutrition among small maize farmers and their children. According to the Organization for Economic Cooperation and Development, U.S. grain farmers receive an average subsidy of $29,000, roughly 120 times the average annual income of these small Filipino maize farmers. The international grain companies are therefore able to transport maize halfway around the world and still offer it at prices equivalent to half the costs of production. Local production of rice is also threatened by the new policies of economic liberalization. The area in the Philippines devoted to maize and rice is expected to shrink by half in the next few years, which would dispossess large numbers of Filipino smallholders in the absence of alternative sources of income (Watkins 1997). Why worry whether Filipino rice farming is sustainable when it is internationally uncompetitive?

It is not easy to fend off the powerful lobbies of the world trade organizations in the name of local socio-cultural survival. But perhaps scientists interested in sustainability can pave the way for a more generous future by educating others to look beyond the monetary and calorific value of food, by systematically exposing the web of human relations, the social and cultural landscape within which any farming system (even that of the American Midwest, Friedmann 1990) operates, and by insisting upon the advantages of a "virtuous spiral" that helps rural populations to help themselves, arming them at least to some degree against the predations of global agribusiness.

## References


Allen P, editor. 1993a. Food for the future: conditions and contradictions of sustainability. New York: John Wiley & Sons Inc.

Allen P. 1993b. Connecting the social and the ecological in sustainable agriculture. In: Allen P, editor. Food for the future: conditions and contradictions of sustainability. New York: John Wiley & Sons Inc. p 1-16.

Altieri MA. 1993. Sustainability and the rural poor: a Latin American perspective. In: Allen P, editor. Food for the future: conditions and contradictions of sustainability. New York: John Wiley and Sons Inc. p 193-209.

Berque A. 1990. Nihon no fûkei, seiô no keikan, soshite zôkei no jidai [Comparative history of the landscape in East Asia and Europe]. Tokyo: Kodansha.

Braudel F. 1992. The identity of France. Vol. II. People and production. Translated by Sian Reynolds. New York: Harper Perennial. (1st French edition 1986, Paris: Eds. Arthaud.)

Bray F. 1984. Agriculture. Vol. VII, Part 2. In: Needham J. Science and civilization in China. Cambridge: Cambridge University Press.

Bray F. 1986. The rice economies: technology and development in Asian societies. Oxford: Basil Blackwell. (Re-issued 1994, Berkeley, Calif., USA, University of California Press.)

Bray F. 1994. Agriculture for developing nations. Scientific American, July 1994, p 18-25.

Bray F. 1997. Technology and gender: fabrics of power in late imperial China. Berkeley, Calif. (USA): University of California Press.

Bray F, Métailié G. n.d. Who was the author of the Nongzheng quanshu? In: Jami C, Liefrinck P, editors. Xu Guangqi (1562-1633): scholar and statesman.

Byres TJ. 1991. The agrarian question and differing forms of capitalist agrarian transition: an essay with reference to Asia. In: Breman J, Mundle S, editors. Rural transformation in Asia. Delhi: Oxford University Press. p 3-76.

Chen H, Wang D. 1983. Bu nongshu jiaoshi [Annotated edition of the Supplemented Treatise on Agriculture of 1658]. Beijing: Nongye Press.

Elvin M. 1973. The pattern of the Chinese past. London: Eyre Methuen.

Francks P. 1983. Technology and agricultural development in pre-war Japan. New Haven, Conn. (USA): Yale University Press.

Friedmann H. 1990. Family wheat farms and third world diets: a paradoxical relationship between unwaged and waged labor. In: Collins JL, Gimenez M, editors. Work without wages: domestic labor and self-employment within capitalism. Albany, N.Y. (USA): SUNY Press. p 193-213.

Friedmann H. 1993. After Midas's feast: alternative food regimes for the future. In: Allen P, editor. Food for the future: conditions and contradictions of sustainability. New York: John Wiley & Sons Inc. p 213-234.

Frossard D. 1994. Peasant science: farmer research and Philippine rice development. PhD dissertation. University of California, Irvine. Irvine, Calif., USA.

Goto J. 1993. Rural revitalization in Japan. Unpublished PhD dissertation. University of California, Los Angeles. Los Angeles, Calif., USA.

Goto J, Imamura N. 1993. Japanese agriculture: characteristics. institutions, and policies. In: Tweeten L, Dishon CL, Chern WS, Imamura N, Moroshima M, editors. Japanese and American agriculture: tradition and progress in conflict. Boulder, Colo. (USA): Westview Press. p 11-29.

Gourou P. 1936. Les paysans du delta tonkinois: étude de géographie humaine. Paris: Mémoires de l'Ecole Française d'Extrême-Orient.

Harriss J. 1991. Agriculture/non-agriculture linkages and the diversification of rural economic activity: a South Indian case study. In: Breman J, Mundle S, editors. Rural transformation in Asia. Delhi: Oxford University Press. p 429-457.

Hayami A, Tsubouchi Y, editors. 1989. Economic and demographic development in rice producing societies: some aspects of East Asian economic history, 1500-1900. Tokyo: Keio University. (Contains seven papers by Japanese authors in addition to those in Hayami and Tsubouchi 1990.)

Hayami A, Tsubouchi Y, editors. 1990. Economic and demographic development in rice producing societies. Proceedings of the Tenth International Economic History Congress, Leuven, August 1990, Session B-3. Leuven (Belgium): Leuven University Press.

Henry Y. 1932. Economie agricole de l'Indochine. Hanoi: Gouvernement Général de l'lndochine.

Huang PCC. 1990. Peasant family and rural development in the Yangzi Delta, 1350-1988. Stanford, Calif. (USA): Stanford University Press.

Islam R. 1986. Non-farm employment in rural Asia: issues and evidence. In: Shand RT, editor. Off-farm employment in the development of rural Asia. Canberra (Australia): ANU, National Centre for Development Studies.

Kada R, Goto J. 1993. Present issues of sustainable land use systems and rural communities in Japan. In: Tweeten L, Dishon CL, Chern WS, Imamura N, Moroshima M, editors. Japanese and American agriculture: tradition and progress in conflict. Boulder, Colo. (USA): Westview Press. p 31-50.

Kahn J. 1980. Minangkabau social formations: Indonesian peasants in the world economy. Cambridge: Cambridge University Press.

Le TC, Rambo AT, with Gillogly K, editors. 1993. Too many people, too little land: the human ecology of a wet rice-growing village in the Red River Delta of Vietnam. Honolulu, Haw. (USA): East-West Center Occasional Papers of the Program on Environment No. 15.

Liu T-j. 1990. Rice culture in South China, 1500-1900: adjustment and limitation in historical perspective. In: Hayami A, Tsubouchi Y, editors. Economic and demographic development in rice producing societies. Proceedings of the Tenth International Economic History Congress, Leuven, August 1990, Session B-3. Leuven (Belgium): Leuven University Press. p 50-68.

Mellor J, Johnston BF. 1984. The world food equation: interrelations among development, employment and food consumption. J. Econ. Lit. 22:531-574.

Moore RH. 1990. Japanese agriculture: patterns of rural development. Boulder, Colo. (USA): Westview Press.

Morishima M, Aita Y, Nakagawa M. 1993. Food consumption in Japan. In: Tweeten L, Dishon CL, Chern WS, Imamura N, Moroshima M, editors. Japanese and American agriculture: tradition and progress in conflict. Boulder, Colo. (USA): Westview Press. p 141-156.

O'Connor J. 1993. Is sustainable capitalism possible? In: Allen P, editor. Food for the future: conditions and contradictions of sustainability. New York: John Wiley & Sons Inc. p 125-138.

Ohnuki-Tiemey E. 1993. Rice as self: Japanese identities through time. Princeton, N.J. (USA): Princeton University Press.

Ozawa K. 1993. A new phase for rice in Japan: production, marketing and policy issues. In: Tweeten L, Dishon CL, Chern WS, Imamura N, Moroshima M, editors. Japanese and American agriculture: tradition and progress in conflict. Boulder, Colo. (USA): Westview Press. p 367-376.

Perdue P. 1987. Exhausting the earth: state and peasant in Hunan, 1500-1850. Cambridge, Mass. (USA): Harvard University Press.

Perkins DH. 1969. Agricultural development in China, 1368-1968. Edinburgh: Edinburgh University Press.

Rawski ES. 1972. Agricultural change and the peasant economy of South China. Cambridge, Mass. (USA): Harvard University Press.

Report of the Expert Consultation on Sustainable Rice Production in Asia and the Pacific. 1996. Bangkok, 29-31 October.

Robertson J. 1991. Native and newcomer: making and remaking a Japanese city. Berkeley, Calif. (USA): University of California Press.

Salazar R. 1992. Community plant genetic resources management: experiences in Southeast Asia. In: Cooper D, Vellvé R, Hobbelink H, editors, Growing diversity: genetic resources and local food security. London: Intermediate Technology Publications.

Shi Z. 1990. The development and underdevelopment of agriculture during the early Qing period (1644-1840). In: Hayami A, Tsubouchi Y, editors. Economic and demographic development in rice producing societies. Proceedings of the Tenth International Economic History Congress, Leuven, August 1990, Session B-3. Leuven (Belgium): Leuven University Press. p 69-88.

Smith TC. 1959. The agrarian origins of modern Japan. Stanford, Calif. (USA): Stanford University Press.

Smith TC. 1988. Native sources of Japanese industrialization. Berkeley, Calif. (USA): University of California Press.

Sperling L, Loevinsohn ME. 1995. New division of labor between farmers and breeders unites conservation and development. Diversity 11(3):5-7.

Thrupp LA. 1993. Political ecology of sustainable rural development: dynamics of social and natural resource degradation. In: Allen P, editor. Food for the future: conditions and contradictions of sustainability. New York: John Wiley & Sons Inc. p 47-74.

Tweeten L, Dishon CL, Chern WS, Imamura N, Moroshima M, editors. 1993. Japanese and American agriculture: tradition and progress in conflict. Boulder, Colo. (USA): Westview Press.

Watkins K. 1997. Fast route to poverty. Guardian Weekly, 16 February. p 29.

Will P-E. 1994. Développement quantitatif et développement qualitatif en Chine a la fin de l'époque impériale. Ann. Hist. Sci. Soc. 49(4):863-902.

Williams R. 1973. The country and the city. London: Fontana.

## Notes

*Author's address:* Anthropology Department, University of California, Santa Barbara, Santa Barbara, California. Bray@sscf.ucsb.edu

*Citation:* Dowling NG, Greenfield SM, Fischer KS, editors. 1998. Sustainability of rice in the global food system. Davis, Calif. (USA): Pacific Basin Study Center, and Manila (Philippines): International Rice Research Institute.

CHAPTER 5

# Sustainability, food systems, and rice: exploring the interactions

K.A. Dahlberg

This paper seeks to explore the main elements involved in pursuing more sustainable rice systems and cultures and how they fit into and interact with the progressively larger frameworks and structures of regenerative food systems and sustainable development. A number of different analytic, scale, and time horizon issues are involved. These are reviewed in the first section via contextual analysis. Next, a range of existing and emerging social paradigms are reviewed to clarify their fundamentally different assumptions about the nature of society and how these affect policy prescriptions. Several recent food policy studies are reviewed in this light. The third section discusses a number of structural, institutional, and value questions that existing paradigms have not asked or have left unanswered. The fourth section outlines the nature and structure of regenerative food and fiber systems and reviews how they are based on new evaluative criteria involving the health and regenerative capacities of their biological and social systems. This framework is then applied to historical and current rice cultures to outline how rice fits into efforts to create more sustainable food systems in Asia, and how such systems are in turn a central component in pursuing sustainable development internationally. The final section sketches the implications for research of employing a food systems approach within the larger framework of sustainability.

## Theoretical, analytic, and value issues associated with sustainability

The basic theoretical approach used here, "contextual analysis," is one that draws upon a range of work in natural and human evolution as well as hierarchy theory in ecology. This approach stresses the importance of systematically examining real-world evolution and its different level processes by analyzing different scale systems over different time horizons. In both natural and human evolutionary theories, the time frame is typically multicentury, the scope global, and the units of analysis broad-gauge. In natural evolution, we can speak at this level of analysis only about species and their interactions. We cannot speak of populations or individuals. Equally, when anthropologists speak of the "great transitions"—from hunting and gathering societies to agricultural to urban to industrial societies—they can speak only of total societies, not of their various sectors—such as agriculture. To do so shifts the level of analysis down a notch, to what I have called "the developmental time frame" (Dahlberg 1979), which is roughly comparable to successional theory in ecology, that is, a time frame that examines more specific developments over roughly a century. More detailed analyses can be done by using a "policy time frame" of roughly a decade. (Recent work in ecology, and specifically the emerging field of long-term ecological research, is making much more explicit the specific natural phenomena, and concepts, that are relevant to different time frames. See the discussion and figures in Magnuson [1990].) It is important to be fully aware that as we shift up and down, there are inevitable trade-offs between the amount of detail that can be captured versus the overall scope that can be covered. (Metaphors of different scale maps or of zoom lenses give a good sense of the trade-offs between detail and scope that can be captured at any given scale or focal length.)

The necessity of employing different concepts and units of analysis for each time frame and level of analysis underlies what ecologists call "hierarchy theory." But it is also crucial at each level of analysis to include social and technological subsystems along with natural subsystems. This broader approach is termed "contextual analysis" (Dahlberg 1979, 1993). It should be noted that the term "contextual" does not carry overtones of governance and/or dominance by a superior elite from the top down that "hierarchy" does. Indeed, the main thrust of much of the literature on hierarchy and sustainability is that it is the health of the lower level units and systems—whether cells in organs, diverse plants in fields, patches of fields, forest, and wetlands in rural landscapes, or peasants in rural communities—that ultimately determines the health of the "higher" level systems, although certainly the latter can have a significant influence on the health of the former. Figure 1 illustrates one example of different levels of analysis and scales relating to agriculture (adapted from Lowrance et al 1986). (Note that although this figure gives a nice view of agricultural systems found in the United States or Europe, it would need significant modification to apply to Asia or Africa. Villages and social systems would need to be added to the natural features illustrated. Also, technologies are left out.)

Also fundamental to contextual analysis is the use of systems approaches that seek to describe in real space and time the structure and interrelationships of the natural, social, and technological subsystems found at each level of analysis. There is a fundamental difference here between contextual systems and abstract, universal-generalization systems. The latter typically do not include the shape and scale of the various specific structural features that affect real-world distribution patterns. These include topographic features; soil and vegetation patterns; the daily, monthly, and seasonal cycles; and the institutions and technological systems that crucially affect the flows, rates, and qualities of energy, materials, and information distributed throughout the various systems and subsystems. (In seeking to analyze the real-world evolution and distribution of phenomena in space and time, natural history, human histories, and mapping approaches and metaphors are often used in contextual analysis. But it also seeks to go beyond case studies, useful as they may be, to analyze patterns and structures and their changes over time. Thus, although contextual analysis is not

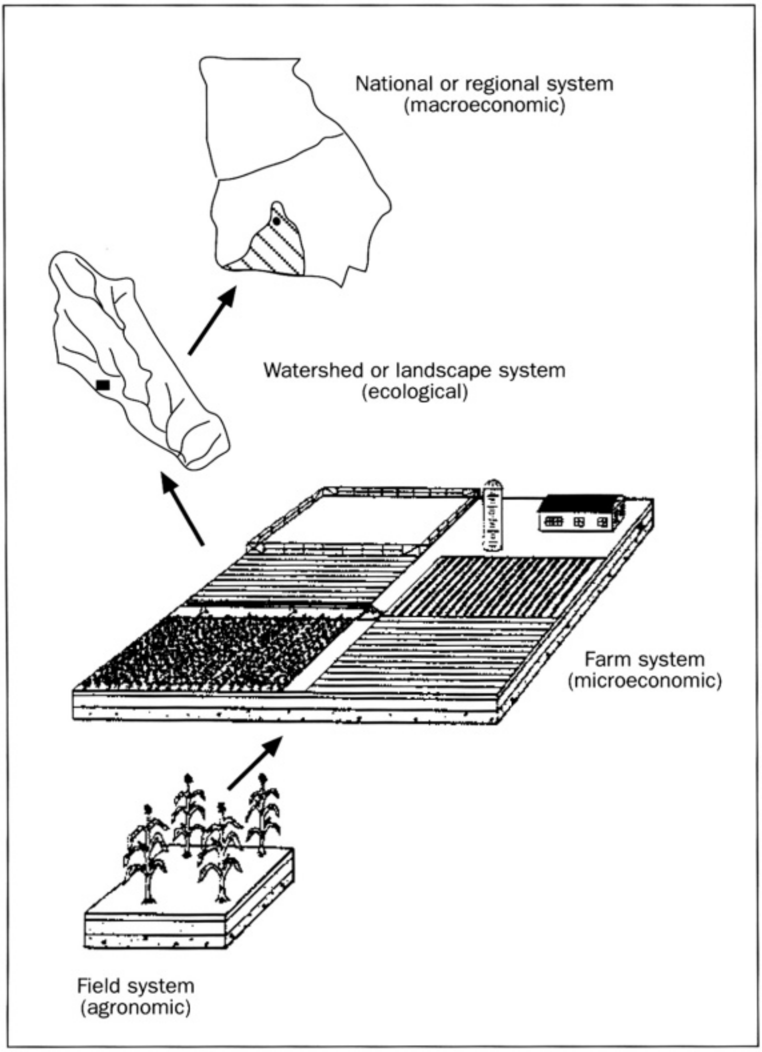



**Fig. 1.** The hierarchical nature of agricultural systems.

as detailed and precise as a case study, it offers broader readings than case studies and more accurate readings than abstract universal-generalization models based on reductionist approaches that employ aggregated and averaged data. Obviously, it requires more thought, data gathering, and analysis as well.)

In biological systems, such structural characteristics are crucial in terms of survival. Diverse structures (that is, ecosystems or habitats characterized by many distinct species and populations widely distributed in space) offer more resilience and adaptability. In contrast to evolutionary tendencies for biological systems to become more complex, industrial societies have increasingly simplified and exploited both social and natural systems—replacing structural diversity and complexity with monocultures arranged in very *complicated* patterns, something that is often confused with *complexity.*

This distinction helps us to sort out in structural terms how traditional societies and agricultural systems have been simplified and disrupted through the spread of both industrial society and industrial agriculture (Dahlberg 1990). This diffusion has been made possible by the massive use of fossil fuels, something that has caused significant environmental disruption and pollution. Most importantly, this simplification and disruption is leading to significant losses of cultural and biological diversity around the world. Although simplified industrial and monocultural cropping systems can be quite productive over the shorter term, they are neither resilient nor adaptive and their complicated (as distinct from complex) structure makes them vulnerable to disruptions or macro changes. This, plus their undermining of their own resource bases (renewable resource systems and informal family and community support systems), means that they are taking us in unsustainable directions.

Another key aspect of contextual analysis is its inclusion of technological structures and systems. Actually including these is difficult because our analytic lenses have been clouded by two powerful social myths: (1) that individual technologies are neutral; although (curiously), (2) the general aggregation and elaboration of technologies lead to progress. These myths also provide important ideological support to powerful interests in society by masking the real-world distributional impacts and costs of new technologies and projects. Thus, attempts to analyze and assess the social and environmental impacts of technological structures and systems are resisted. It is clear, however, that technologies and technological systems are not neutral because (1) they reflect the natural and social environments in which they were developed, (2) they have different organizational and resource prerequisites that vary significantly according to their scale, and (3) they reflect their design goals and principles (Dahlberg 1989). Only by understanding the nonneutral characteristics and distributional impacts of specific technological structures and systems can we evaluate whether or not they contribute to the health and regenerative capacity of any larger system.

Human ecological approaches and contextual analysis also suggest a different approach to values. On the one hand, every general approach contains an underlying set of values. For example, it is clear that biological and ecological concepts, such as resilience and adaptability, reflect a disciplinary valuing of both species and life processes. On the other hand, just as different concepts and units of analysis are needed to understand and describe relevant phenomena and relationships at any given level, different value concepts and issues are also found at each level.

What this means is that the values and goals relevant for the health and regenerative capacity of the system need to be consciously specified and included at each level of analysis. This contrasts sharply with conventional positivistic approaches that posit that there are universal, value-free concepts that cut across time, space, and levels. A common problem with conventional universal-generalization models is that they often falsely or inappropriately project or impose what are useful concepts and units of analysis at one level of analysis or time frame onto other levels or time frames. In addition, they are often based on or assume Western values and industrial goals (because most models emanate from Western culture and industrial paradigms). For example, the transfer of industrial agricultural technologies involves not only the often inappropriate transfer of temperate-zone technologies into tropical or semiarid regions but also the integral assumption upon which the technology was built—that the economic goal of the technology is to increase labor efficiency (relevant in the U.S. or Europe), not energy, resource, or capital efficiency (which is more relevant in Asia and Africa). (For a detailed discussion, see Dahlberg [1989]; the same points are made in regard to Asia by Bray [1986].)

At root, issues of sustainability are about how to preserve cultural diversity and biological diversity at all levels from the many threats to them. These threats occur at a time when we may well be in the early phases of a "grand transition" from industrial society to some new type of social structure—post-fossil-fuel societies. This transition challenges three different levels of values and institutions: (1) basic Western cultural values, (2) industrial values and categories of thought, and (3) the institutions that have grown up around them. Each of these needs to be examined.

As Robertson (1979) has pointed out, the deepest Western cultural assumptions and values relate to Judeo-Christian beliefs regarding man's separation from, and dominance over, nature and to the supposedly natural hierarchical and patriarchal structure of society. Later, during the often painful transition away from medieval values and structures to modernity, the Reformation and Renaissance revived and added important assumptions about the primacy of rationality, secularism, and science. The early utopian visions of the Industrial Revolution added strong urban and technological biases and myths (see Mumford 1970, Mannheim 1936). These have stressed the value of artifact, industry, urban life, and formal organization and have neglected or undervalued nature and natural processes, food and agriculture, rural regions and life, and informal systems. (The former spheres of activity have often been associated with male roles, whereas many of the latter have been associated with female roles. Many of the alternative movements that started emerging in the 1970s have sought to change this balance and to give much greater value to nature and the environment, to local informal systems involving food and agriculture, to rural life, and to women's activities.)

Growing out of these Western and industrial values is a set of industrial institutions and categories of thought. As Douglas (1986) has argued, the institutions in each society not only reflect and reproduce its larger cultural values but also largely structure and maintain the categories of thought deriving from those values. In the Western setting, these include such categories of thought as functional specialization, efficiency, and individualism (or atomism). Our industrial institutions (which provide and perpetuate these industrial categories of thought) are in turn strongly reinforced by the development of new technological systems based on those same categories of thought (computers, information networks, new property systems). The challenges to those seeking to move industrial society toward sustainability are thus diverse: they must seek to change values and their associated institutions and reinforcing technologies. (The difficulties involved today are much greater than those found historically in paradigmatic and institutional change in science. This is because of the development since World War II of a large science establishment that is of great importance to both government and business. Institutional change is especially difficult in the applied sciences—medicine, engineering, and agriculture—where, in addition to professional interests, a host of associated vested economic interests are found.)

Because the term "sustainable" is general, carries overtones of homeostasis, and is subject to co-optation, I prefer the term "regenerative." It points much more directly to the basic reproductive and generational questions that are crucial to the health of individuals, habitats, populations, and societies over longer time horizons. It also suggests an ongoing and evolutionary process of change and continuity. (Just as each of us as an individual carries the genes of our parents [continuity], they are combined in a new way [change]. The process is similar between generations. Each generation seeks to socialize the next into its cultural and social assumptions and values [continuity]. Yet each new generation grows up in its own historical context where wars, depressions, social movements, etc., can strongly shape its particular values and views [change]. For a discussion, see Marías [1970]. It is important to bring in the co-evolutionary processes and dynamics that occur over time between social systems and natural systems. For detailed discussions of this in the Amazon, see Norgaard [1981], whose more recent work examines these interactions more generally as well as their implications for our visions of the future [Norgaard 19941].)

By focusing on the health and regenerative capacity of natural and social systems, we are also forced to consider how they depend on the fluctuations, availability, and purity of nutrients and the great biochemical cycles of which they are a part. Thus, the term "regenerative" requires a consideration of the negative impacts of industrial societies in terms of pollution, the simplification and/or destruction of habitats, and climate change. Programs to recycle physical materials, to reduce dependence on nonrenewable sources of energy, and to reduce pollution and other impacts of fossil-fuel-intensive systems must become an integral part of the search for more regenerative systems. Although integral, they are secondary in the sense of needing to be structured and evaluated in terms of how they best contribute to maintaining or increasing the regenerative capacity of living systems.

## Dominant and alternative social paradigms

We need to clearly identify the background assumptions of general social paradigms so that we can better assess both the value issues and the scientific and methodological issues involved in trying to understand sustainable development generally, and regenerative food systems in particular.

Most paradigms—conventional and alternative—are based on Western world views, although in some alternative paradigms significant reinterpretations are suggested. Within the Western tradition, rather different structures of thought are found—with the most striking differences found between universal-generalization models and contextual approaches. These largely correspond to the conventional/alternative breakdowns discussed below. Within each, however, there are also variations that depend on the social and political values of particular schools of thought. All of these factors shape each school's description of the way the world works and what its problems are. These, in turn, lead directly to their forecasts, and the prescriptions they make for what is needed now and in the future.

Hughes (1985) has done a nice job of illustrating these points for two major types of paradigms: political economy and ecology paradigms. For the first, Hughes (1985) lists three major schools, each with its own description of the world, forecasts, and prescriptions (Table 1). For the second, Hughes (1985) lists a conventional and an alternative paradigm (Table 2).

These tables show the links between the descriptions, forecasts, and prescriptions of different social paradigms and schools of thought. In his text, Hughes also discusses both the larger world views and the disagreements within schools that revolve around differing social and political values and judgments.

### Efforts to broaden and synthesize

More recent work has sought a broader-gauge synthesis of many of the above elements. One synthesis is found in a summary table in the proceedings of the first meeting of the International Society for Ecological Economics (Costanza 1991), which compares conventional economics and ecology (Table 3). Although this excellent table covers many important dimensions, it does not deal with one very important concept—place. An increasing number of writers seeking greater decentralization and local self-reliance as a more energy-efficient and environmentally sound approach to sustainable development have also stressed the need for individuals and groups to have strong connections—through a sense of community—with the specific environment where they can live, carry out, and largely govern their livelihoods (Orr 1994, Sale 1985). Many critiques of conventional development theory also argue for a focus on sustainable rural development that includes maintaining and strengthening existing rural groups and peasants.

Gotlieb (1996) has brought many of these themes together in a wide-ranging critique of the disfunctions of modernization and a set of proposals for what he calls "endogenous recovery regions." ("The Endogenous Recovery Regions concept presupposes that *place-specific social, economic, and ecological conditions are interrelated to and contingent on one another and that they collectively define an integral entity"* [Gotlieb 1996, emphasis in the original]. Gotlieb devotes several chapters to how Kurdistan should be considered as an endogenous recovery region.) Gotlieb employs very different conceptions of space and place than typically found. Conventional abstract conceptions facilitate planning, governing, and administration by large

**Table 1. Political economy paradigms.**

| | Important descriptive statement | Typical forecasts | Prescriptions |
|---|---|---|---|
| Liberals | Free markets are mutually beneficial. | The North-South gap will narrow significantly over the next few decades. | Globally, government intervention in domestic and international economies should be minimized. |
| | Economic growth occurs in stages. | The population problem will solve itself. | Price mechanisms will solve energy and food problems. |
| Internationalists | Free markets are unequally beneficial. | The North-South gap will close only slowly. | Western nations should assist less-developed countries with foreign aid and trade concessions. |
| | Growth stages can be accelerated with help. | Population might overwhelm resources in some countries and create a poverty cycle. | |
| | | Agriculture and energy problems are long term and might worsen. | |
| Radicals | "Free" markets are controlled by the rich. | The North-South gap will not close. | LDCs must either break away from the international system or change via revolution. |
| | Developed countries hold LDCs in perpetual poverty. | (Therefore) the population issue cannot be resolved.<br>(And therefore) agriculture and energy will remain problems, especially for LDCs. | |

formal organizations—public and private. Often centralized, these powerful organizations typically weaken or overpower local efforts at endogenous development. In contrast, Gotlieb develops a contextual concept—"life-place"—to stress the need to describe and understand the specific environments, cultures, ethnic groups, communities, forms of livelihood, and work found in specific regions.

Useful as these attempts at synthesizing emerging alternative paradigms are, neither Costanza nor Gotlieb deals extensively with technological structures or systems.

**Table 2. Political ecology paradigms.**

| | Important descriptive statement | Typical forecasts | Prescriptions |
|---|---|---|---|
| Modernists | Mankind increasingly controls its environment. | Materially and technologically progress will continue. | A policy of *laissez innover* should be adopted with respect to most technology; active research and development programs should be sponsored. |
| | Technology is the key to a better future. | Environmental problems will be solved. | |
| | | Resource limitations will be overcome. | |
| Neotraditionalists | Environment is more complex than often believed. | Material and technological progress will prove unsatisfying. | Control and selectivity should be exercised with respect to new technologies. |
| | Lifestyles consistent with human values are the keys to a better future. | Environmental problems will appear faster than they can be addressed. | Economic "throughput" (input of resources and output of pollutants) should be minimized to conserve resources and limit environmental impact. |
| | | Resource scarcities will intensify. | Control population. |

**Table 3. Comparison of "conventional" economics and ecology in *Ecological Economics.***

| | Conventional economics | Conventional ecology | Ecological economics |
|---|---|---|---|
| **Basic world view** | **Mechanistic, static, atomistic** | **Evolutionary, atomistic** | **Dynamic, systems, evolutionary** |
| | Individual tastes and preferences taken as given and the dominant force. The resource base viewed as essentially limitless due to technical progress and infinite substitutability. | Evolution acting at the genetic level viewed as the dominant force. Humans are just another species but are rarely studied. | Human preferences, understanding, technology, and organization coevolve to reflect broad ecological opportunities and constraints. Humans are responsible for understanding |

Table continued

**Table 3 continued.**

| | Conventional economics | Conventional ecology | Ecological economics |
|---|---|---|---|
| | | | their role in the larger system and managing it sustainably. |
| **Time frame** | **Short** | **Multiscale** | **Multiscale** |
| | 50 yr max., 1–4 yr usual | Days to eons, but time scales often define noncommunicating subdisciplines. | Days to eons, multiscale synthesis. |
| **Space frame** | **Local to international** | **Local to regional** | **Local to global** |
| | Framework invariant at increasing spatial scale, basic units change from individuals to firms to countries. | Most research has focused on smaller research sites in one ecosystem, but larger scales have become more important. | Hierarchy of scales. |
| **Species frame** | **Humans only** | **Nonhumans only** | **Whole ecosystem including humans** |
| | Plants and animals only rarely included for contributary value. | Attempts to find "pristine" ecosystems untouched by humans. | Acknowledges interconnections between humans and rest of nature. |
| ***Primary* macro goal** | **Growth of national economy** | **Survival of species** | **Ecological economic system** |
| ***Primary* micro goal** | **Maximum profits** (firms) **Maximum utility** (individuals) | **Maximum reproductive success** | **Sustainability must be adjusted to reflect system goals** |
| | All agents following micro goals leads to macro goal being fulfilled. External costs and benefits given lip service but usually ignored. | All agents following micro goals leads to macro goal being fulfilled. | Social organization and cultural institutions at higher levels of the space/time hierarchy ameliorate conflicts produced by myopic pursuit of micro goals at lower levels. |
| **Assumptions about technical progress** | **Very optimistic** | **Pessimistic or no opinion** | **Prudently skeptical** |
| **Academic stance** | **Disciplinary** | **Disciplinary** | **Transdisciplinary** |
| | Monistic, focus on mathematical tools. | More pluralistic than economics, but still focused on tools and techniques. Few rewards for integrative work. | Pluralistic, focus on problems. |

## The need to develop political technology paradigms

This need is highlighted in Schumacher's (1973) observation that: "Today the main content of politics is economics, and the main content of economics is technology. If politics cannot be left to the experts, neither can economics and technology." The extensive literature on appropriate technology (see especially Darrow and Saxenian 1993 and Stewart 1987) as well as various critiques of technology and industrial society (see Pacey 1983, Illich 1973, and Mumford 1970) suggest that several political technology paradigms and schools of thought within them should be put into a typology. While not providing this, Table 4 does illustrate the different-level concepts and values found between dominant industrial and alternative technological paradigms.

## Application to policy models

The broad social paradigms mentioned above have been analyzed because they strongly shape both development theories and policy models. There have been many descriptions of the evolution of development theories (see, for example, Cooper and FitzGerald 1989, Gotlieb 1996). But policy models relating to food, agriculture, and sustainability are fairly recent. To varying degrees, they still rely primarily on conventional assumptions and are contextual only in narrow environmental terms. Three relatively recent efforts deserve some comment because they show changes in the thinking of policy researchers who deal with food and agriculture.

There has been some discussion by national and international agencies of the different levels that need to be considered. In a series of studies over the years, the Food and Agriculture Organization of the United Nations (FAO) has sought to portray the larger trends and issues that affect food and agriculture. The earlier studies (1981 and 1988) depended largely on a single-scenario model. Changes in assumptions about (lower) rates of economic and population growth led to major changes in projected demand for agricultural production between the 1981 and 1988 reports (see Alexandratos 1988). The basic weaknesses from a contextual perspective of the abstract and universal model then used include: it employed a universal-generalization approach based on functional specialization; it followed conventional Western assumptions about the nature of development; it used primarily an economic model based on aggregate data for what is grown and traded in the formal economy; and it developed only one scenario. Its larger goals related primarily to increasing productivity, although some concern was expressed about environmental impacts in a chapter on "sustainable growth in production." The commentary, however, discussed the importance of various structural issues such as land reform, the need for increasing farmer participation in research, changing the balance of urban/rural subsidies, etc.

The 1995 FAO study, *World Agriculture: Toward 2010* (Alexandratos 1995), represents a number of major advances over the earlier ones. It identifies two underlying themes: (1) the need for enhanced food security and nutrition, and (2) the need for improved sustainability of agricultural and rural development. The first theme is still the primary concern. But it may well be that the presence of a new director general as

**Table 4. Levels of technology and values.**

| Level | Dominant industrial | | Alternative | |
|---|---|---|---|---|
| | Concepts | Underlying values | Concepts | Underlying values |
| Household | "Time savers" | Convenience; family | Appropriate technologies | Self-reliance, family, community |
| Village/ neighborhood | ? | Convenience; neighbors | Appropriate technologies | Self-reliance, neighbors, community |
| Cities | Dynamic cities | Economic growth as part of national and international economies | Healthy cities | Health, community self-reliance, participation |
| Regions | ? | ? | Bioregionalism, rural develop ment | Self-reliance, participation, sustainable economies |
| Sectors | Industrial, hard path | Production/productivity, power/ control/management | Decentralized, soft path | Energy and resource efficiency |
| Agriculture and food systems | Industrial agriculture, biotech, precision farming | Production/ productivity, control/ management | Organic and sustainable | Evolution, adaptation, participation |
| National | Sustainable development | Economic growth, S&T[a] $\rightarrow$ progress | Sustainable development | Equity, biological and cultural diversity |
| International | Global village, megatechnologies, "free" trade | Economic growth, S&T $\rightarrow$ progress | A globe of villages, sustainable development, "regenerative" trade | Equity, biological and cultural diversity |
| Global | Space our last frontier | S&T $\rightarrow$ progress, human dominance | Gaia hypothesis | Equity, participation, conservation of biological and cultural diversity |

[a] S&T = science and technology.

well as the 1992 United Nations Conference on the Environment and Development and the 1992 International Conference on Nutrition broadened the study to include both new topics and a much stronger emphasis on sustainability. There is also a much greater recognition that a range of forces and factors interact to affect what happens in different regions and types of economies. Surprisingly, there are seen to be no "insurmountable resource and technology constraints at the global level that would stand in the way of increasing world food supplies by as much as required . . . ." (Alexandratos 1995). This is recognized, however, to not apply to marine-capture fisheries, where real resource and technology limits are now operating. Finally, there is a clear recognition throughout that the only way to reduce food insecurity in the longer term is to reduce poverty. For the many low-income countries that depend primarily on agriculture for income and employment, the primary development goal is argued to be genuine rural development that reduces both poverty and the pressures to practice environmentally unsustainable agriculture.

A much more detailed and policy-oriented approach is the International Food Policy Research Institute's initiative, "A 2020 Vision for Food, Agriculture, and the Environment." (This initiative seeks to take the kinds of policy research that IFPRI has been doing since 1975 and put them into new formats that will reach a much wider audience. A wide range of background books, discussion papers, briefs, and syntheses, as well as a newsletter, have been commissioned and published. Also, a major conference was held in 1995 to give the initiative a highly visible launching.) The initiative seeks to develop an action plan for eradicating hunger and malnutrition while maintaining the environment. Production trends and needs are identified through IFPRI's International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), which simulates trade patterns and supply and demand for 17 commodities among 35 countries and regions. These have been combined with population projections, estimates of foreign aid, amounts of investment in agricultural research, assessments of water shortages, etc., to come up with a set of general and regional policy recommendations (IFPRI 1995). These models and studies tend to suffer from many of the same general problems of the FAO study, but have the advantage—given their much more specific policy focus—of dealing with a range of structural issues. Also, the inclusion and integration of environmental issues is much greater than with the FAO studies.

A recent study by the Netherlands Scientific Council for Government Policy (NSCGP 1995) explores the policy implications of sustainability by using risk as an organizing concept. Different assumptions about risks to nature versus risks to society are used to develop a four-cell matrix based on different levels of production (high or low), changes in production systems (adaptation or basic reform), and changes in levels of consumption (high or low). Four resulting "action perspectives" (utilizing, saving, managing, and preserving) are then applied to five problem areas: world food, energy, nature, raw materials, and water. (The world food scenario is interesting because it includes submodels for globally oriented and locally oriented agricultural systems. Also, it includes submodels for Western and moderate diets [based on the amount of meat in the diet]. Unfortunately, the overall scenarios are structured in terms of optimizing production and do not include the many social and institutional barriers to this, so that their optimistic results regarding global food availability ". . . mainly indicate the potential, not the most probable, development" [NSCGP 1995].) This approach shows the significance of different assumptions about the relationships between humans and nature. It also suggests that we need to examine our assumptions about the longer-term adaptive capacities of both nature and society.

The above review of emerging social paradigms and policy models for sustainability has been meant to be illustrative, not comprehensive. It has tried to identify the basic elements underlying different conventional and alternative approaches that need to be spelled out as part of clarifying the basic cultural, structural, and values assumptions involved. Many other examples could—and at some point should—be evaluated similarly.

## Unanswered questions on sustainability

The social paradigms discussed above leave several types of questions unasked or unanswered. These need to be identified and explored to pursue more sustainable/regenerative societies and food systems. Otherwise, we risk generating partial or false descriptions and remedies for our situation.

Three fundamental questions can be asked for each of our three time frames. First, how can we learn the lessons of the past regarding sustainability so as to maintain and strengthen existing regenerative systems and elements? Second, how do we better understand our current top-heavy and nonsustainable industrial institutions so as to be in a position to transform them in the direction of sustainability? (For purposes of this paper, the common assumption that these questions can be dealt with by society will be accepted. We hope that a combination of social and institutional change will permit a muddling through to sustainability. Scenarios derived from top-down planning/management models and based on optimistic assumptions regarding high degrees of human control over society and nature seem much less plausible. None of this is to say that various disaster scenarios should not be studied as well.) Third, how do we develop visions for genuinely sustainable societies as well as generate support for them?

*In an evolutionary time frame,* several subquestions are involved in addressing these basic questions.

1. *Lessons of the past.* How does the maintenance of cultural and biological diversity relate to keeping our evolutionary options open? What were the key elements involved in "great transitions" of the past? What have been the impacts of colonialism in terms of sustainability? And in regard to the rice cultures and economies of Asia, have the basic natural and social requirements of rice cultivation shaped a unique type of social structure? If so, has its evolution and the addition of various modern industrial elements changed the basic socio-natural structures of rice cultivation? Bray (1986) argues convincingly that a unique type of social structure did emerge over the centuries and that its basic elements are

still relevant. (Bray's masterful historical and anthropological analysis shows the weaknesses and misreadings of Eurocentric models as applied to Asia and, more importantly, provides a careful reading of the major forces at play in Asian rice economies over time.)

2. *Transformation.* Does the creation of an increasingly interconnected network of global infrastructure systems increase or decrease the ability of human societies to make the transition to post-fossil-fuel societies? (Although a great deal of work on contemporary systems is being done under the umbrellas of global change and human dimensions of global change, little of it is aimed at identifying the elements of sustainability or the dynamics of transformation.) How do we best understand population, resource, and environmental dynamics and their linkages to global infrastructures? (At a minimum, the anthropocentric focus of demographers needs to be transcended to include livestock and other relevant plant, animal, and disease-causing populations that interact with humans, crops, and livestock [see Crosby 1994]. Similarly, it can be argued that the "population explosion of artifacts" [cars, TVs, computers, etc.] also needs to be included [see Dahlberg 1996b].) Would a decentralization of infrastructure patterns increase the ability of societies to adapt? Can current infrastructures—in whatever form—be maintained without fossil fuels?
3. *Values, visions, and social support.* Will Western/industrial institutions and values and their concomitant categories of thought continue to dominate development patterns? If so, are the resulting monocultural visions and structures of a global village at all compatible with the requirements of sustainability?

In a developmental time frame of roughly a century, other subquestions are involved—both general ones relating to the spread of industrial institutions and more specific ones relating to the structures of the traditional rice cultures and economies of Asia.

1. *Lessons of the past.* How has the resource and energy intensity of industry and agriculture changed over the past couple of centuries? What have been the costs and benefits of this (including all of the externalities that standard analyses generally neglect)? What have been the changes in institutions and organizations that have affected sustainability—especially in property and land tenure systems? What have been the differential impacts of different types of technology?
2. *Transformation.* Many of the important questions involved here were raised in the World Commission on Environment and Development's report Our Common Future (WCED 1987), such as, How can we reduce population growth rates in the poor countries and high consumption levels in the rich, while preserving biodiversity and pursuing a new type of development that is sustainable and equitable? (Most references to the report's definition of sustainable development leave out the portions dealing with equity. The full definition is: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts: the concept of 'needs,' in particular the essential needs of the

world's poor, to which overriding priority should be given; and the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs" [WCED 1987].) Which technological systems and structures enhance or reduce the prospects for transforming industrial institutions? What feedback exists between technological systems and organizational patterns? (The work done on energy by Lovins [1977] and Lovins and Lovins [1982] offers one useful way to sort out the structural aspects and implications of energy systems. They argue that the structure of these systems is more important than the type or source of energy used. Thus, "hard path" solar energy systems [solar satellites or solar farms] are similar to other large-scale, capital-intensive, centralized, and sophisticated energy production systems, such as nuclear or coal-fired plants. All, they argue, are very inefficient in energy, capital, and social terms compared with the smaller-scale, more decentralized, labor-intensive, and locally repairable "soft path" technologies they favor.) What are the implications of the recent and dramatic expansions of property systems to include much larger areas of the oceans and all life-forms? (A number of basic questions emerge from the expansion of the jurisdiction of coastal states over their adjacent oceans and seas as well as from the extension of state ownership to include biodiversity resources and corporate ownership to include genetically engineered life-forms.) Will these transform the basic relationships between humankind and nature? What are the moral implications of this? Will these new property systems be combined with new technologies and centralized organizations (public or private) to create new "manufacturing aristocracies" that will undermine democracy and its adaptability. (Tocqueville warned in 1835, at the beginning of the Industrial Revolution, of the dangers of a new "manufacturing aristocracy" arising that would weaken democracy and degrade and exploit workers and farmers [see Tocqueville 1966]. The degree of national and international concentration in food and agriculture is increasing to where most inputs and outputs are increasingly controlled by oligopolies. For the trends within the U.S., see Constance et a1 [1990]. For a profile of one, if not the world's largest, private corporation—Cargill—see Kneen [1995].)

3. *Values, visions, and social support.* One underlying question here is whether visions can be developed that offer on the one hand some larger world view based on respect for the primacy of life and living systems, while on the other hand respecting local cultural and biological diversity. Is a major shift in values possible whereby economic and technological matters will once again become subservient within larger-value frameworks? (Valuable lessons from the past regarding how economics became primary, and thus how we might seek a strategy to once again "embed" economics within larger social frameworks can be found in Polanyi [1944].) Can an ecological theory of trade be developed that would be based on a recognition that all natural systems and creatures have differential boundary systems (biological and social) that permit passage of health-maintaining or health-enhancing materials and restrict or limit passage of unhealthy ma-

terials? (Developing an ecological economic theory along these lines will be difficult. But without such a theory, it will be difficult to challenge current free-trade ideologies that do not recognize health, safety, and environmental issues, much less sustainability issues [see Daly 1993].) Similar types of questions can be asked about the impact of changing educational and communications structures—where the globalization of communications technologies spreads both Western and industrial values.

In a policy time frame, we come to more familiar types of questions. Typically, however, they are framed in terms of Westerd/industrial assumptions.

1. *Lessons of the past.* These are generally understood in terms of short time horizons and economic issues. They are also often politicized because groups choose those lessons that point in the direction they want to go. Appeals are made to currently strong values and beliefs: that there are technological solutions; if not, then more education or participation is the answer. Preventive measures and organizational reform are much harder to promote. Remaining are several tough questions—which apply whether the topic is development, democratization, or sustainability: How do we sort out real issues and lessons in a time of fundamental change? How do we effectively share these lessons and apply them?
2. *Transformation.* Many more transformations that expand or elaborate on the industrial model have been proposed and actively pursued than transformations toward sustainability. (Economic growth models, free-trade ideologies, the Green Revolution, biotechnology, intellectual property rights, various space ventures, computers, the telecommunications revolution, all these and more strengthen industrial institutions and categories of thought. Environmental impact assessments, technology and social impact assessments, ecological economics, sustainable agriculture, appropriate technologies, recycling, local food systems, plus a host of social and environmental movements all have some potential for transforming industrial institutions, but have yet to do so in any major way.) What sorts of economic and technological policies can be developed that will deal effectively with problems such as increasing concentrations of wealth and power? How does this apply in the food and agricultural sector? How do we shift from externally driven development to endogenous development?
3. *Values, visions, and social support.* If we are in a time of transition, new types of values and visions will be needed. What sort of genuinely possible futures do we want and who will have what voice in shaping those visions? Who is included in the “we”? Is it a nationality? Is it only those currently living? Are only humans included? Is there some way to include consideration for future generations—something analogous to the “seventh generation” principle used by some Native American tribes? What does “voice” mean? What sort of participation is required to both educate people on the issues and give them a stake in pursuing the changes required for sustainability?

We can draw several major conclusions from the above discussion. One is that structural and institutional issues are both crucial and neglected. Another is that large-scale systems are powerful and their power makes organizational and institutional reform very difficult. Finally, a careful analysis of different levels of values and how they interact with and shape institutions and analytic approaches is needed. (For a broad-gauge overview of these issues, see Bennett and Dahlberg [1990].) At this point, however, we need to turn to a discussion of regenerative food systems.

## Regenerative food systems and rice cultures

This section will first review the general nature of regenerative food systems. It will then look at rice cultures in Asia to apply these general aspects to a specific context.

Many of the general debates and issues surrounding the concept of sustainability were prefigured in debates about sustainable agriculture. These sought to take agricultural analysis and policy beyond productivity and economics alone to include three other ''e's'' as well: ecology, ethics, and equity. (These correspond to the three definitions that Douglass [1984] identified: [1] sustainability as long-term food sufficiency, i.e., food systems that are more ecologically based and that do not destroy their natural resource base; [2] sustainability as stewardship, i.e., food systems that are based on a conscious ethic regarding humankind's relationship to other species and to future generations; and [3] sustainability as community, i.e., food systems that are equitable or socially just. As the turmoil in several poor regions of the world demonstrates, food systems cannot be sustainable if there are gross maldistributions of land, wealth, and power. This is one of the main reasons for focusing on the increasing concentration of oligopolistic power in the food and agriculture industries. For other discussions of definitions of sustainable agriculture, see Harwood [1990] and Dahlberg [1991].) Those debates have also led to an increasing recognition that sustainable agriculture needs to be placed within the broader scope of food systems (see Dahlberg 1993).

Regenerative food systems operate at a number of levels. They also interact with broader natural, societal, and technological systems. In terms of how they are evaluated, a fundamental shift is needed toward health criteria. That is, we need to evaluate the health and regenerative capacity of both the larger and smaller systems that have a great bearing on the health and regenerative capacity of food systems—at each level from the household to the neighborhood, the regional, national, etc. Moving to systems approaches also requires a fundamental shift in thinking. Rather than focusing primarily on production systems (as is the case with agriculture, forestry, grazing, and fisheries), the entire food system must be included. This means examining the wide range of processes, issues, and institutions relating to food production, processing, distribution and access, preparation, use (health and nutrition; food safety), recycling, and waste disposal, plus food storage at each stage (Fig. 2).

As emphasized in the discussion above, at different levels, different things need to be examined. At the global level, four major areas need attention (Dahlberg 1996a): (1) the explosion of livestock and human populations, (2) linkages between fossil fuel use, agriculture, and global climate change, (3) the loss of cultural diversity and biodiversity, and (4) the growth of global inequality. Internationally, a host of ques-

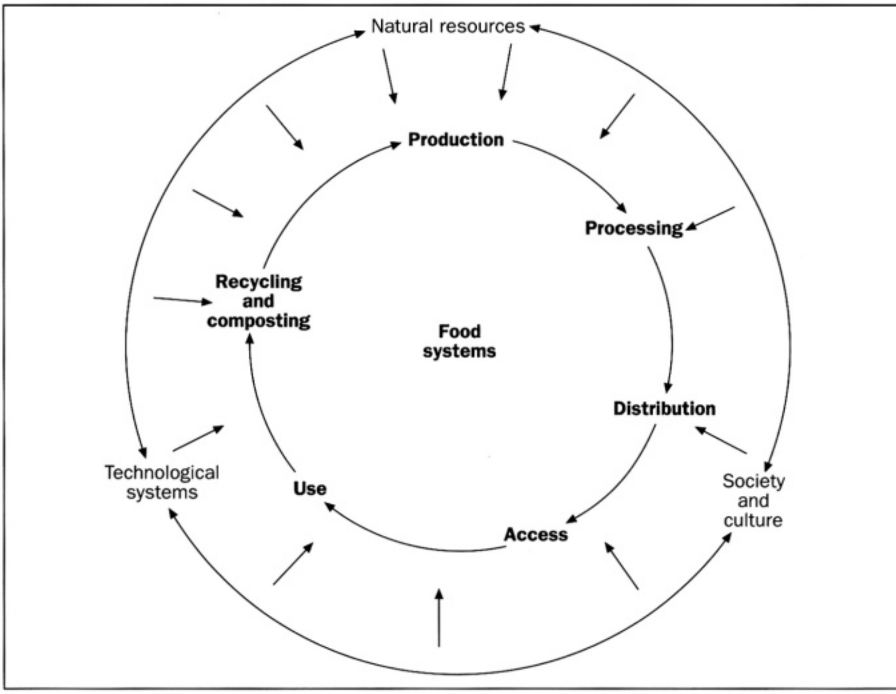


**Fig. 2.** The elements of food systems and the larger influences upon them.

tions were raised above regarding infrastructure and institutional trends. At regional scales, food and fiber systems should really be seen as renewable resource systems that include a range of infrastructure patterns, land tenure and land use practices, and trade patterns—all interwoven into a crazy quilt of what are now defined separately in national statistics as agriculture, forestry, and fisheries (often inconsistently and with a strong commodity bias; see Dahlberg [1992] for a full discussion). How these larger regions fit into international and global patterns and requirements for sustainability also needs to be examined.

A variety of approaches and models have been developed to deal with regional and lower-level food systems. Figure 3 (adapted from Rambo et al [1986], as found in Sajise [1988]) provides a useful general depiction of the different approaches and how their focus varies by level. It is also important to place these approaches within a framework of resource management. (Wilson and Morren [1990] provide a stimulating overview of "soft systems" approaches to understanding the resource management requirements of agriculture that draws heavily on the model developed at Hawkesbury College [now the University of Western Sydney]. Uphoff [1986] is particularly good in describing how the different types of local institutions need to be developed to fit the distinct structures and requirements of such different develop-

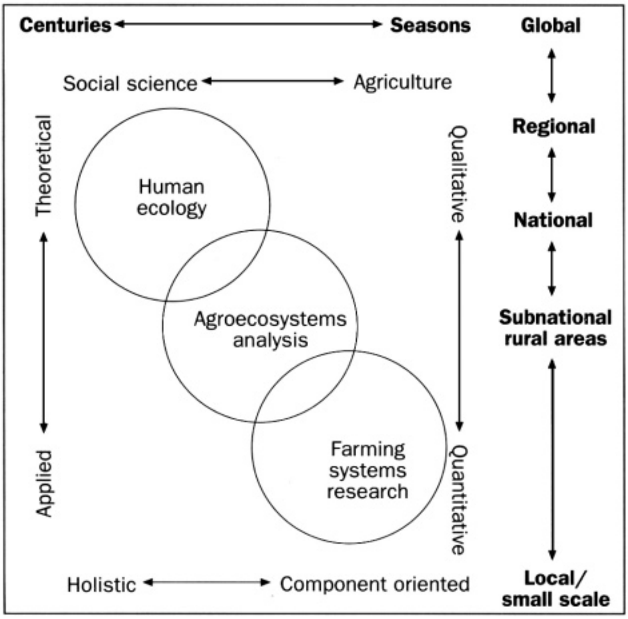



**Fig. 3.** Conceptual approaches to food and agricultural systems. (Adapted from Rambo et al 1986, as found in Sajise 1988.)

ment arenas as rural infrastructure development, primary health care development, and local agricultural development.)

Developing specific contextual understandings of rice systems and how they fit into these larger levels and systems is a major challenge. Indeed, it is a challenge to assemble good conventional analyses of rice systems, something done nicely in Barker et al (1985). But it is important to move beyond Western and Eurocentric understandings and histories of agriculture. Reinterpretations based on Asian histories and assumptions using human ecological approaches are needed.

A model for this is Bray (1986). A few of the major lessons to be found in her work are that the evolution of rice systems in Asia was quite varied and dynamic over the millennia; many of today's "new" approaches to development and technological change had similar precursors historically; the basic productiveness of rice and the labor and crop management requirements for growing wetland rice create social and farming structures that favor smaller production units (family-size farms)—whatever the land tenure system; rice systems contain a tension between individualism and the cooperation required to keep irrigation networks functioning smoothly; rice systems are based more on skills-oriented technologies than mechanical technologies; and that, because of this, greater cropping intensity and production are possible, thereby increasing the numbers that can be supported in a given area. This makes it all the more important to carefully assess the impacts of different proposed technologies on rice farmers and rural regions. Throughout, Bray also stresses that local adaptations to climate, soils, latitude, social customs, market location, and local political patterns are needed to obtain sustainable local (and national) economies and societies.

At lower levels of analysis, we find some interesting and innovative work that applies agroecosystems research, farming systems research, and cropping systems research to rice systems. (For details, see Conway [1985], Rerkasem and Rambo [1988], and Rerkasem and Ganjananpan [1985].) Figure 4 offers one of the few models in which organizational, institutional, and technological factors relating to local resources, food, and agriculture are specifically included.

It is clear from the geographic scale of Asian rice systems, from the numbers of people that they support, and from their long history that they are crucial to the future of global food and agriculture. The largely successful environmental and social adaptation and sustainability of these systems over the centuries also make clear that an improved understanding of them will enable us to maintain and/or strengthen their sustainable elements and will be central to the world's larger efforts to move in more sustainable directions.

## Implications for research

The main implications for research on sustainability are as follows. (For a detailed discussion of the specific types of research needed in industrial countries at each level of analysis, see Dahlberg [1993].) First, there is a great need to go beyond abstract models and systems. This involves locating in real space and time the relevant structures of specific natural, social, and technological systems. Just as specific topographies, soils, and vegetation patterns distribute rainfall by channeling different amounts, rates, and qualities of water to different places, specific organizations, institutions, and technological systems will distribute and channel the results of their activity in highly specific and variable patterns. Thus, at each level, the key structures and factors that affect the distribution of energy, materials, and information need to be identified and the patterns of distribution summarized. (As noted earlier, contextual analysis does not seek the high detail of case studies, although these can be invaluable sources of information. Rather, it seeks to include the major structures that strongly shape distribution patterns in space and time and at different levels and scales.) Likewise, it is important to try to identify changing structures and patterns of distribution over time to better understand the sources of change. (Natural and social systems show important variations that derive from temporal cycles—whether daily, monthly, seasonal, or annual. On the importance of seasonal changes, see Gill [199l] and Ulijaszek and Strickland [1993].)

Second, at each level it is crucial to make our various assumptions, values, and beliefs as explicit as possible. They are always present, but often in an unconscious or hidden form. They shape our understandings of the world as well as our visions and goals. The failure to become more aware of Western/industrial biases has led to serious misreadings of other cultures in general and of rice cultures in particular. Our understandings of rice cultures have also been seriously distorted by our beliefs in technological progress and the neutrality of technologies. While the process of be-

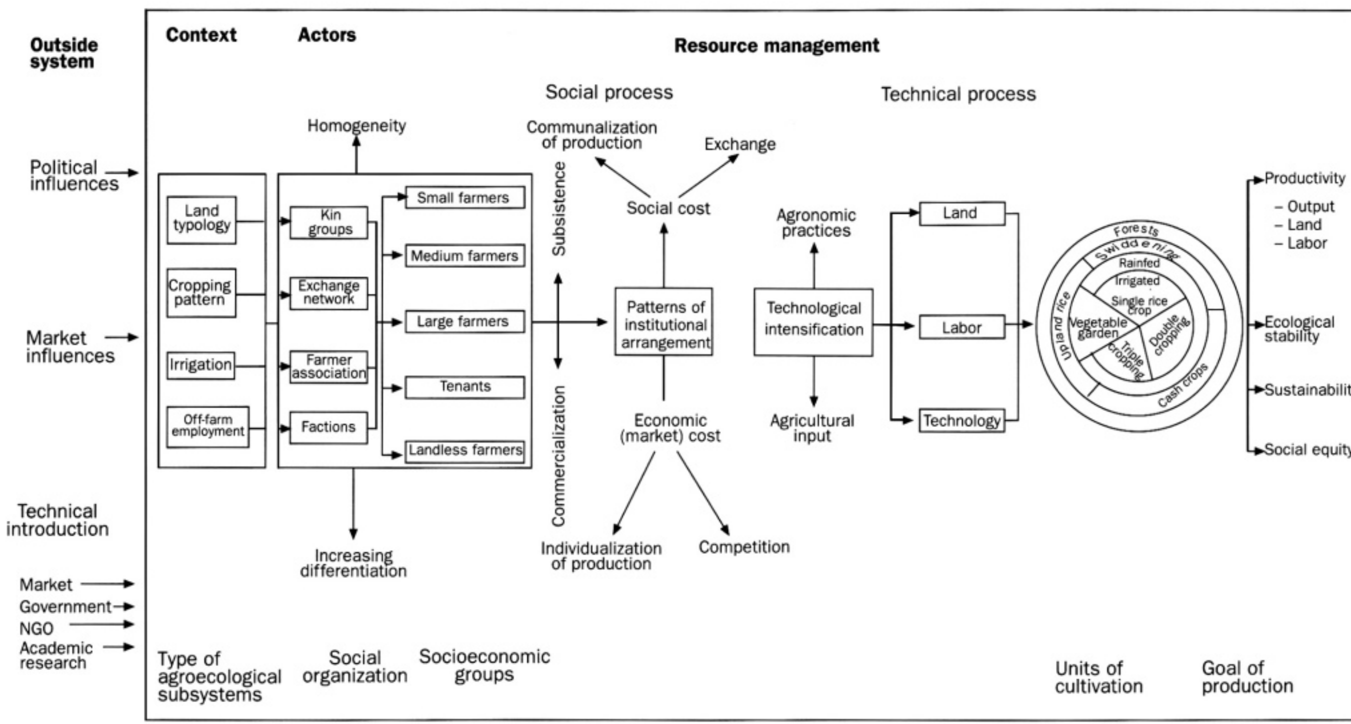



**Fig. 4.** Conceptual framework of resource management: processes and village-level factors. (From Rerkasem and Ganjanapan 1985, as found in Sajise 1986.)

coming more explicitly aware of our beliefs thus requires better analysis of technological systems, it also ultimately requires painful reevaluation of individual as well as social values, goals, and priorities. (Similar painful reevaluations are in process for racial and gender beliefs and practices.)

Third, and bringing the first two points together, we need to be cautious about the models we use. In analyzing something like rice sustainability, we really need several models that explicitly include different structural and value assumptions. Also, we need a hierarchy of different models, each with its own structure and processes, each operating on a different time scale. One of the central difficulties of any formal model is the issue of transformation. Most formal models deal with transformation only in terms of "black boxes" that show inputs and transformed outputs, but not the processes or structures involved in the transformation. (In Forrester's [1961] industrial dynamics language, these black boxes are auxiliary variables that are part of the flow-rate description, but are separated from that symbol because they can be most clearly described independently as a mathematical function of two inputs. In Odum's [1971] and Odum and Odum's [1976] symbolic energy language, these black boxes are receptors-components [typically a green plant] capable of receiving radiant energy and converting it to another form. Beyond this problem is another—that these formal systems are structured primarily in terms of flows [i.e., quantities]. Issues of quality and how quality can enhance, maintain, degrade, or destroy living components of systems are difficult to deal with. It would seem that models based on health [broadly defined] would be better able to deal with these issues than either industrial- or energy-based models.) To make policy recommendations that could help move societies toward sustainability, analysts need to be able to identify what key changes within the black boxes at one level would also help transform structures at the next level.

Fourth, as mentioned earlier, different levels of analysis and time frames require different concepts and different types of data. Likewise, different value assumptions will lead to an emphasis or neglect of various processes and the data associated therewith. One of the basic difficulties of moving toward a food systems approach is that both more and different types of data are needed compared with the agricultural production data of the formal sector that are often simply aggregated at regional and international levels. The latter will tell us how much food is being produced for sale internally and for trade, but tell us nothing about either the informal sector or the relative health of the renewable resource systems on which we all depend.

In conclusion, the long-range implications for research on pursuing sustainability as broadly understood from a contextual perspective are the same as for societies at large—major organizational and institutional changes and transformations are required if potentially massive disruptions and/or collapse are to be avoided. In terms of research, these changes and transformations are linked to the overriding need for research establishments to restructure to be able to effectively address the issues raised by sustainability and contextual approaches. Thus, researchers and research establishments have to see themselves as both part of the problem and (potentially) part of the solution. They can no longer see themselves either as sources of a single universal truth or as detached observers. They will have to become part of the process of adaptive change. To do this, academics and researchers will need to become aware of, and rethink, what they are truly professing and practicing. Then, basic choices will have to be made. Will they maintain their current basic allegiance to a discipline, their nationality, or an ideology? Or will they seek a broader pursuit of preserving and enhancing the variegated richness of interacting life-forms as they evolve over multiple generations?

## References


Alexandratos N, editor. 1988. World agriculture: towards 2000. An FAO Study. New York: New York University Press.

Alexandratos N, editor. 1995. World agriculture: towards 2010. An FAO Study. New York: John Wiley & Sons.

Barker R, Herdt RW, with Rose B. 1985. The rice economy of Asia. Washington, D.C. (USA): Resources for the Future.

Bennett JW, Dahlberg KA. 1990. Institutions, social organization, and cultural values. In: Turner BL II, editor. The Earth as transformed by human action: global and regional changes over the past 300 years. Cambridge: Cambridge University Press. p 69-86.

Bray F. 1986. The rice economies: technology and development in Asian societies. Oxford: Basil Blackwell.

Constance DH, Gilles JL, Heffeman WD. 1990. Agrarian policies and agricultural systems in the United States. In: Bonanno A, editor. Agrarian policies and agricultural systems. Boulder, Colo. (USA): Westview Press. p 9-75.

Conway G. 1985. Agroecosystem analysis. Agric. Admin. 20(1):31-55.

Cooper C, FitzGerald EUK, editors. 1989. Development studies revisited. London: Frank Cass.

Costanza R, editor. 1991. Ecological economics: the science and management of sustainability. New York: Columbia University Press.

Crosby A. 1994. Germs, seeds, & animals: studies in ecological history. Armonk, N.Y. (USA): M.E. Sharpe.

Dahlberg KA. 1979. Beyond the Green Revolution: the politics and ecology of global agricultural development. New York: Plenum.

Dahlberg KA. 1989. The value content of agricultural technologies and their effect on rural regions and farmers. J. Agric. Ethics 2(2):87-96.

Dahlberg KA. 1990. The industrial model and its impacts on small farmers: the Green Revolution as a case. In: Altieri M, Hecht SB, editors. Agroecology and small farm development. Boca Raton, Fla. (USA): CRC Press. p 83-90.

Dahlberg KA. 1991. Sustainable agriculture: fad or harbinger? Bioscience 45(5):337-340.

Dahlberg KA. 1992. Renewable resource systems and regimes: key missing links in global change studies. Global Environ. Change 2(2): 128-152.

Dahlberg KA. 1993. Regenerative food systems: broadening the scope and agenda of sustainability. In: Allen P, editor. Food for the future: conditions and contradictions of sustainability. New York John Wiley and Sons. p 75-102.

Dahlberg KA. 1996a. World food problems: making the transition from agriculture to regenerative food systems. In: Pirages D, editor. Building sustainable societies: a blueprint for a post-industrial world. Armonk, N.Y. (USA): M.E. Sharpe. p 257-274.

Dahlberg KA. 1996b. Population dynamics and global change: the need for new conceptual maps. GeoJournal 39(3):311-320.

Daly HE. 1993. The perils of free trade. Sci. Am. 269 (November):50-57.

Darrow K, Saxenian M. 1993. Appropriate technology sourcebook. Stanford, Calif. (USA): Volunteers in Asia.

Douglas M. 1986. How institutions think. Syracuse, N.Y. (USA): Syracuse University Press.

Douglass GA. 1984. Agricultural sustainability in a changing world. Boulder, Colo. (USA): Westview Press.

Forrester JW. 1961. Industrial dynamics. Cambridge, Mass. (USA): M.I.T. Press.

Gill GJ. 1991. Seasonality and agriculture in the developing world. Cambridge and New York: Cambridge University Press.

Gotlieb Y. 1996. Development, environment, and global disfunction: towards sustainable recovery. Delray Beach, Fla. (USA): St. Lucie Press.

Harwood RR. 1990. A history of sustainable agriculture. In: Edward CA et al, editors. Sustainable agricultural systems. Ankeny, Iowa (USA): Soil and Water Conservation Society. p 3-19.

Hughes B. 1985. World futures: a critical analysis of alternatives. Baltimore, Md. (USA): Johns Hopkins University Press.

IFPRI (International Food Policy Research Institute). 1995. A 2020 vision for food, agriculture, and the environment: the vision, challenge, and recommended action. Washington, D.C. (USA): IFPRI.

Illich I. 1973. Tools for conviviality. New York: Harper & Row.

Kneen B. 1995. Invisible giant: Cargill and its transnational strategies. London and East Haven, Conn. (USA): Pluto Press.

Lovins A. 1977. Soft energy paths. Cambridge, Mass. (USA): Ballinger.

Lovins A, Lovins LH. 1982. Brittle power. Andover, Mass. (USA): Brick House.

Lowrance R, Hendrix PR, Odum EP. 1986. A hierarchical approach to sustainable agriculture. Am. J. Altern. Agric. 1(4):169-173.

Magnuson JJ. 1990. Long-term ecological research and the invisible present. Bioscience 40:495-501.

Mannheim K. 1936. Ideology and utopia. New York: Harcourt, Brace.

Maxias J. 1970. Generations: a historical method. University, Ala. (USA): University of Alabama Press.

Mumford L. 1970. The myth of the machine: the pentagon of power. New York: Harcourt, Brace, and Jovanovich.

Norgaard RB. 1981. Sociosystem and ecosystem coevolution in the Amazon. J. Environ. Econ. Manage. 8(Spring):238-254.

Norgaard RB. 1994. Development betrayed: the end of progress and a coevolutionary revisioning of the future. London: Routledge.

NSCGP (Netherlands Scientific Council for Government Policy). 1995. Sustained risks: a lasting phenomenon. Reports to the Government No. 44. The Hague: The Netherlands.

Odum HT. 197 1. Environment, power, and society. New York: John Wiley & Sons.

Odum HT, Odum E. 1976. The energy basis for man and nature. New York: McGraw-Hill.

Orr DW. 1994. Earth in mind. Washington, D.C. (USA): Island Press.

Pacey A. 1983. The culture of technology. Oxford: Basil Blackwell.

Polanyi K. 1944. The great transformation. New York: Farrar & Rinehart.

Rambo AT, Chantalakhana C, Seetisarn M. 1986. Mid-term evaluation report. Farming Systems Research Sub-project, Khon Kaen University Research Development Project. Khon Kaen, Thailand.

Rerkasem K, Ganjananpan A. 1985. The management of land, labor, and agricultural technology in Chiang Mai rice-growing villages: research design for an interdisciplinary study. In: Sajise RE, Rambo AT, editors. Agroecosystem research in rural resource management and development. College, Laguna (Philippines): University of the Philippines at Los Baños. p 126-133.

Rerkasem K, Rambo AT, editors. 1988. Agroecosystem research for rural development. Chiang Mai (Thailand): Multiple Cropping Center, Chiang Mai University, and the Southeast Asian Universities Agroecosystem Network (SUAN).

Robertson J. 1979. The sane alternative: a choice of futures. St. Paul, Minn. (USA): River Basin.

Sajise PE. 1988. Agroecosystem analysis: the SUAN approach. In: Rerkasem K, Rambo AT, editors. Agroecosystem research for rural development. Chiang Mai (Thailand): Multiple Cropping Center, Chiang Mai University, and the Southeast Asian Universities Agroecosystem Network (SUAN). p 9-31.

Sale K. 1985. Dwellers in the land: the bioregional vision. San Francisco, Calif. (USA): Sierra Club Books.

Schumacher EF. 1973. Small is beautiful: economics as if people mattered. New York: Harper Torchbooks.

Stewart E 1987. Macro-policies for appropriate technology in developing countries. Boulder, Colo. (USA): Westview Press.

Tocqueville A de. 1966. Democracy in America. Mayer JP, Lerner M, editors. New York: Harper & Row.

Ulijaszek SJ, Strickland SS, editors. 1993. Seasonality and human ecology. 35th Symposium Volume of the Society for the Study of Human Biology. Cambridge and New York: Cambridge University Press.

Uphoff N. 1986. Local institutional development. West Hartford, Conn. (USA): Kumarian Press.

WCED (World Commission on Environment and Development). 1987. Our common future. Oxford: Oxford University Press.

Wilson K, Morren GEB Jr. 1990. Systems approaches for improvement in agriculture and resource management. New York: Macmillan.

## Notes

*Author's address:* Department of Political Science, Western Michigan University, Kalamazoo, MI 49008. dahlberg@wmich.edu

*Citation:* Dowling NG, Greenfield SM, Fischer KS, editors. 1998. Sustainability of rice in the global food system. Davis, Calif. (USA): Pacific Basin Study Center, and Manila (Philippines): International Rice Research Institute.

# Part III:
# Rice Production Systems: Challenges for Rice Research in Asia

CHAPTER 6

# Challenges for rice research in Asia

K.S. Fischer

Rice is the staple food for nearly half the world's people, most of them living in Asia, many of them among the poorest in the world. The crop is grown primarily in the humid and subhumid tropics and subtropics. It is an important agricultural commodity in many less developed countries of Asia, where land is intensely cultivated, forests are disappearing, and water is becoming increasingly scarce.

The rice research community, including the International Rice Research Institute (IRRI), has been successful, so far, in helping provide this staple food to expanding populations. But alarming indications of continuing poverty and malnutrition, unabated environmental degradation, and high population growth are pressuring the thin margin between the crop's supply and demand. Rice scientists continue to believe that they can find ways to grow enough rice for the expanding population for the coming decades, sustain higher rice production, and maintain the natural resource base and protect the environment.

Meeting these challenges will require continued investment in agricultural research and development. In a world of shrinking resources to generate advances in science and technology, however, research planners and managers face a daunting task. They must identify and develop research methods that use resources efficiently to achieve high-quality outcomes. This is the task that international agricultural research centers—including IRRI, its partners in global rice research, and national programs—must assume.

For IRRI, the task is to spearhead a "double Green Revolution"—an increase in grain supplies with protection of the environment—in rice, the staple food on which nearly two and a half billion people already depend. That number will almost double within our children's lifetime to more than four billion.

The central question for rice research is how to balance the need for ever-greater food production, at prices that poor consumers can afford and that are profitable to farmers, with critical concerns about protecting our natural resources and the environment for generations to come.

In countries where rice is the dominant crop and primary staple food, the welfare of consumers depends on the crop's availability and quality, and on the level and stability of its price. The welfare of producers depends on crop productivity, production costs, and input-output prices. These sometimes conflicting interests can be reconciled through rice research that increases yields, improves the efficient use of scarce natural resources (labor, land, fertilizer, water, etc.), and reduces the unit costs of production. Thus, cost-reducing technologies enable society to supply rice at affordable prices to consumers while maintaining farmers' profits and incentives to produce rice, even at lower prices.

About 80 million ha of rice—more than half the harvested area—is grown under irrigated conditions worldwide. Farm yield under irrigation ranges from 3 to 9 t $ha^{-1}$. The irrigated rice ecosystem contributes 75% of global rice production and provides the predominant source of marketable surpluses for growing populations, particularly the urban poor. With a favorable production environment assured by water control, the likelihood of farmers adopting improved technology is high compared with those farming in other rice ecosystems.

Irrigated rice is grown in bunded, puddled fields with assured irrigation, with one crop a year (in the subtropics and temperate zones) or more than one crop annually (in the humid and subhumid tropics). Some areas with relatively low yields receive only supplementary irrigation in the wet season. Nearly 24 million ha are intensively cultivated and double-cropped in southern China, Indonesia, the Philippines, Vietnam, Bangladesh, and southern India. The water needs of the dry-season crop are large because of high evapotranspiration and low rainfall. High solar radiation, minimal cloud cover, and low pest incidence help give the dry-season crop a much higher yield than that of rice grown in the wet season.

Rainfed lowland rice grows in bunded fields that are flooded for at least part of the cropping season to water depths of less than 50 cm for more than 10 consecutive days. Because most production of rainfed lowland rice depends on erratic rainfall, farming is diverse and unpredictable. Farmers usually raise one crop of rice and subsequently grow pulses, oilseeds, or forage crops if residual soil moisture permits their establishment.

About 25% of the world's rice land, nearly 40 million ha, is rainfed. This ecosystem contributes 18% of the global rice supply. Average yields are low because farmers grow mainly traditional varieties. The potential for increasing production is great for this ecosystem. Nearly 12 million ha of rainfed lowland rice are in Thailand and Myanmar, where traditional low-yielding varieties are grown because their high grain quality is valuable in the export market. Research on improving grain quality in high-yielding modern cultivars could encourage investment in irrigation and conversion of some rainfed land to irrigated rice land. The increasing demand for high-quality indica rice in the world market can be met from this subecosystem if production can be expanded.

Most of the rainfed rice area is in South Asia, where the crop suffers from drought, poor drainage, and flooding, often within the same season. The current land tenure system, poor infrastructure, and poverty lead farmers to practice low-input farming, which constrains growth in productivity of land and labor.

Upland rice is grown on 17 million ha, about 12% of the global rice area, but the ecosystem contributes only 4% of global rice production. Yields are low and the ecosystem is highly diverse. Some farmers use slash-and-burn techniques to grow rice mixed with other subsistence crops on the slopes of hills. A large portion of the upland area consists of level fields on the Chhotonagpur and Chhatisgarh plateaus of eastern India and in newly cleared forests in the humid tropics of Latin America and Africa. In Brazil, which has 18% of the global upland rice area, the crop is grown on farms that are large, commercial, and mechanized. Under these conditions, yields can be as high as 6 t $ha^{-1}$.

More than 20 million ha of rice land in the active floodplains of major river deltas in South and Southeast Asia are subject to uncontrolled flooding from river overflows and tidal fluctuations. Rice is virtually the only crop that can be grown during the wet season. In recent years, the area under floating rice in deep-flooded areas has declined by more than 2 million ha. Low-cost irrigation facilities are enabling farmers to grow high-yield, low-risk boro rice (harvested in spring) during the dry season.

When the first Green Revolution began, only 10–15% of the Asian population lived in urban areas. Most rice consumers were farmers, laborers, and artisans. Production for subsistence guided the adoption of new technologies and growth in rice production. The small amount of surplus generated to meet the nonfarm needs of rice farm households was enough to meet the rice needs of relatively small urban populations.

Today, with growing economic prosperity and rapid urbanization, the situation is different. Nearly 30% of the Asian population already lives in cities, and urban populations may surpass rural populations within the next 25 years. Farmers must generate substantial marketable surpluses to feed urban dwellers. This requirement means that rice cultivation will become much more commercially oriented. Farmers will grow less rice for direct consumption by their own households and more rice in response to market opportunities with potential for higher income. Profit maximization will become the main force that drives rice production. Rice cultivation will become more like any other economic activity, with constant pressure to increase input use efficiency in competition with alternative economic enterprises that use the same resources. Failure to compete will mean diversion of agricultural land and labor to more profitable economic enterprises, and rice production will decline because farmers will not be able to afford to grow the crop.

During the past 30 years, rice production in Asia doubled in response to the adoption of modern varieties, increased investments in irrigation, higher use of fertilizer, and some expansion in cultivated area. In some countries, the problem shifted from coping with rice shortages to disposing of surpluses. In the next 30 years, however, when an increase of at least 50% is needed, the production environment will be quite different. Rice productivity is showing signs of decline, expansion of area for growing rice is limited, investments in irrigation have virtually ceased, increased fertilizer use threatens the environment, and good rice land is being lost to other purposes. The only option left is to increase rice yield of existing lands over the next 30 years.

Increasing rice yield is an exciting challenge to research. We hope that genetic manipulations, breeding strategies, and crop and environmental management techniques will result in continued improvement in crop productivity. Part III of this volume addresses the challenges for rice research in Asia. The following chapter examines the opportunities for and potential of genetic enhancement of rice by improving its physiological processes and tolerance of abiotic stresses in different rice-growing environments. Succeeding chapters deal with the intensification of rice production systems, pests and weeds, resource management for intensive rice systems, and rice in the global environment. Part III concludes with a look at IRRI's new frontier projects in rice research.

## Notes

*Author's address:* International Rice Research Institute (IRRI), P.O. Box 933, 1099 Manila, Philippines. k.fischer@cgnet.com

*Citation:* Dowling NG, Greenfield SM, Fischer KS, editors. 1998. Sustainability of rice in the global food system. Davis, Calif. (USA): Pacific Basin Study Center, and Manila (Philippines): International Rice Research Institute.

CHAPTER 7

# Genetic enhancement of rice yields

S. Peng and D. Senadhira

The yield potential of irrigated rice in the tropics has stagnated at 10 t ha$^{-1}$ since 1966, when the first semidwarf indica variety, IR8, was released. During the past 30 yr, rice improvement efforts have been directed toward incorporating disease and insect resistance, shortening growth duration, and improving grain quality. Because 75% of all rice is produced on irrigated land, breaking the yield ceiling of irrigated rice through genetic improvement has become the top priority in rice research. The yield of current semidwarf varieties is limited largely by dry matter production. It can be improved by modifying the present high-yielding plant type. High DM accumulation coupled with selection of large panicles will lead to an increased sink size (defined as spikelet number per unit ground area). Grain filling has to be improved to convert an increased sink into additional grain yield. Lodging also limits yield, especially at high yield levels. Studies on chemical composition and physical structure governing stem strength are needed. Breeding for the new plant type using tropical japonica germplasm has resulted in a phytotype with increased sink size because of large panicles and fewer unproductive tillers. The yield potential of this new plant type is limited by poor grain filling. Exploitation of hybrid vigor or heterosis through hybrid rice breeding provides a good opportunity for increasing the yield potential of rice in the tropics. Intersubspecific hybridization between indica and japonica varieties has shown higher heterosis for yield than indica/indica hybrids. Hybrids between elite indica varieties and the new plant type tropical japonicas are being developed.

Rainfed rice constitutes about 45% of the total rice-growing area in Asia. The present average yield of 2 t ha$^{-1}$ should be increased to about 4 t ha$^{-1}$ during the next 30 yr. This increase is also essential to release the pressure on irrigated rice. Water- and soil-related stresses are the constraints to increases in rainfed rice production. Tolerance for these abiotic stresses is available in the germplasm. Various combinations of these tolerance traits that can match the many different subecosystems are needed to increase and stabilize yields. The success so far in developing improved varieties tolerant of abiotic stresses has been limited mainly because understanding of the physiological mechanisms and the inheritance of these traits is inadequate, and rapid and reliable techniques for screening genotypes, especially for multiple stresses, are lacking. Some progress has been made in developing tolerance of flooding and salinity. But for drought and other soil stresses, progress has been slight. We urgently need to intensify research on the genetics and physiological mechanisms of tolerance for

abiotic stresses. This research is also essential for exploring new genetic engineering opportunities such as marker-aided selection techniques that seem to offer solutions for breeding rainfed rice.

During the past 30 yr, rice production in Asia doubled in response to the adoption of modern varieties, increased investments in irrigation, higher use of fertilizer, and expansion in cultivated area. In the next 30 yr, however, when an increase of at least 70% is needed, the production environment will be quite different. Rice productivity is showing signs of decline, expansion of area for growing rice is limited, investments in irrigation have virtually ceased, high fertilizer use threatens the environment, and good rice lands are being lost to other purposes. The only option left is to double the rice yield of existing lands over the next 30 yr.

Doubling rice production is an exciting challenge to research. We hope that genetic manipulations, breeding strategies, and crop and environmental management techniques will result in continued improvement in crop productivity. This paper discusses opportunities for and potentials of genetic enhancement of rice by improving its physiological processes and tolerance of abiotic stresses in different rice-growing environments.

## Enhancing yield potential of favorable environments

More than 75% of all rice is produced on irrigated land although irrigated rice land accounts for about 50% of total rice area. Most irrigated lowland paddies are considered favorable for rice production because water and nutrients are not major constraints to rice growth. In tropical Asia, irrigated lowlands in the dry season are more favorable for rice production than in the wet season because of the higher solar radiation in the dry season. The yield potential of current high-yielding varieties grown under favorable environments in the tropics is 10 t ha$^{-1}$ during the dry season and about 7 t ha$^{-1}$ during the wet season. Maximum yield potential has been estimated at 9.5 and 15.9 t ha$^{-1}$ in this region during the wet and dry seasons, respectively, based on the level of solar radiation (Yoshida 1981). It is possible to narrow the gap between the present and maximum yield potential through genetic crop improvement.

Yield potential is determined by the total dry matter (DM) or biomass and the harvest index (HI, a ratio of grain to total DM). Biomass production is a function of photosynthetic rate and duration and respiration rate. Optimum canopy architecture for maximum crop photosynthesis, increased photosynthetic capacity of individual leaves, and delayed leaf senescence for longer photosynthetic duration are effective approaches for increasing biomass production. Harvest index is affected by sink size (which is defined as the number of spikelets per unit ground area), canopy photosynthetic rate during the ripening phase, and grain filling percentage. An increased number of spikelets per panicle and reduced partitioning of DM to unproductive tillers will result in an improved HI. Lodging is a major constraint to yield potential. Biomass production can be enhanced by increasing the input of mineral nutrients if plants have lodging resistance.

The Green Revolution in Asia started in 1966 when IRRI released the first semidwarf indica variety, IR8. This is the most striking example of a quantum jump in yield potential by modifying the plant type. During the 30 yr after the development of the semidwarf plant type, however, only marginal improvements in rice yield potential have occurred. Rice improvement efforts have been directed toward incorporating disease and insect resistance, shortening growth duration, and improving grain quality. To achieve a quantum jump in rice yield potential, we must explore the possibility of further modifying the present high-yielding plant type and the physiological processes governing yield potential. Another approach for increasing the yield potential of rice in the tropics is to exploit hybrid vigor or heterosis through hybrid rice breeding.

## Photosynthesis and 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 al 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. Because it is difficult to increase HI for many cereals (Austin et al 1980), a further increase in yield potential will be attained mainly through increased biomass production. This conclusion is indirectly supported by the fact that a yield of 13.6 t $ha^{-1}$ was achieved with an HI of 0.46 in the subtropical environment of Yunnan, China (Khush and Peng 1996).

At least 90% of DM of higher plants is derived from $CO_2$ assimilated through photosynthesis (Zelitch 1982). Biomass production can be increased through optimized canopy architecture for maximum canopy photosynthesis, improved photosynthetic characteristics of individual leaves, and extended photosynthetic duration.

Canopy photosynthetic rate increases as leaf area index (LAI, a ratio of leaf area to ground area) increases. The crop reaches optimum LAI when canopy photosynthesis levels off. An ideal variety should have a droopy-leaf canopy in the very early vegetative stage to effectively intercept solar radiation. As the crop grows, a plant community with vertically oriented leaves has better light penetration and a higher canopy photosynthetic rate at high LAI. Varieties with erect leaves have a higher optimum LAI than varieties with horizontal leaves (Yoshida 1981). Erect leaves between panicle initiation and flowering are one of the major morphological traits that rice breeders have been selecting for. It was reported recently that V-shape leaf blades reduce mutual shading and increase canopy photosynthesis as do erect leaves (Sasahara et al 1992). Simulation modeling suggests that a steeper slope of the vertical N concentration gradient in the leaf canopy with more N present in the uppermost stratum enhances canopy photosynthesis (Dingkuhn et al 1991). Lowering panicle height increases light interception by leaves and consequently increases canopy photosynthesis (Setter et al 1995). But the adverse effects of lowering the panicles on panicle exsertion and panicle diseases need to be investigated. Austin (1993) argued that no substantial improvement in biomass production could be obtained by selecting for modified canopy morphology because modern varieties are close to the optimum canopy architecture.

The semidwarf plant type reduces susceptibility to lodging at high N inputs and increases HI (Tsunoda 1962). Recent studies, however, indicated that 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 canopy than in the short one (Kuroda et al 1989). If stem strength can be improved, the height of modern rice varieties should be increased to improve biomass production.

Crop physiologists have tried selecting for high single-leaf photosynthetic rate under light saturation ($P_{max}$) in several crop species, but no cultivar has been released from these selection programs (Nelson 1988). Direct selection for $P_{max}$ sometimes resulted in lower yield (Evans 1990). Although genetic variation in $P_{max}$ has been reported in rice, the relationships between photosynthetic capacity and biomass production were poor (McDonald et al 1974). In spite of these problems, the hypothesis that higher $P_{max}$ is necessary for increased yields is still popular (Elmore 1980). Zelitch (1982) stated that the lack of a strong positive relationship is due to measurements of $P_{max}$rather than biological reasons. Austin (1993) believes that genotype × ontogeny and genotype × environment interactive effects on $P_{max}$ cause poor correlation. Traits that are pleiotropically and negatively related to $P_{max}$ may offset any gains from higher $P_{max}$ (Austin 1993). With a better understanding of limiting processes in photosynthesis, advances in measurement methodology, and the advent of biotechnology, which enables the modification of content or activity of individual enzymes, we should reexamine the possibility of enhancing biomass production through improving $P_{max}$.

A linear and positive relationship between $P_{max}$ and leaf N content per unit leaf area was reported for pot-grown (Yoshida and Coronel 1976) and field-grown rice plants (Peng et al 1995). This increase is attributed to the close relationship between leaf N and Rubisco content—the $CO_2$-fixing enzyme of photosynthesis (Makino et al 1984). Modern rice varieties respond quickly to N application by increasing leaf N content because of the high N-absorbing capacity of the root system (Peng and Cassman 1998). High leaf N content, in the meantime, increases tiller production and leaf area expansion, which cause mutual shading and actual reduction in canopy photosynthesis. The concern is how to increase leaf N content without significant increases in tillers and leaf area. Leaf thickness is positively correlated with $P_{max}$ (Murata 1961). A thick leaf has less tendency to expand horizontally and a greater tendency to be erect. After the early vegetative stage, thick leaves are thought to be desirable for improving $P_{max}$.

The yield potential of wheat varieties released by CIMMYT has increased by 0.83% $yr^{-1}$ over the past 30 yr. This increase was mainly attributed to increased stomatal conductance and canopy temperature depression (Fischer 1994). Irrigated rice has a much higher stomatal density and stomatal conductance than wheat (Teare et al 1971, Dai et al 1995), suggesting that $P_{max}$ in irrigated rice plants is unlikely to be limited by stomatal conductance. Small differences in carbon isotope discrimination among varieties and over a wide range of N input levels (S. Peng, unpubl. data) also suggest that there is little chance to improve $P_{max}$ by increasing stomatal conductance for irrigated rice. Other options proposed to increase $P_{max}$ include suppression of photorespiration and reduction of maintenance respiration (Penning de Vries 1991). There is little evidence that photorespiration can be suppressed in $C_3$ plants, and although there is evidence of genetic variation in maintenance respiration, the magnitude of such differences is small (Gifford et al 1984). Penning de Vries (1991) also proposed to increase the flux of $CO_2$ from the soil through the root aerenchyma to the leaves, providing an additional source of $CO_2$ for photosynthesis. This approach is unlikely to be effective if stomatal conductance does not limit photosynthesis in rice.

Horton and Ruban (1992) believe that operational photosynthesis in the field never actually reached intrinsic $P_{max}$. During the course of the day and the entire growing season, photosynthesis operates at $P_{max}$ over a very short period of time. Internal and external factors limit attainment of the full potential of photosynthesis. Internally, photosynthesis can be controlled by the demand for its products—so-called feedback inhibition or sink limitation (Neales and Incoll 1968). Externally, when the light intensity is raised during growth, $P_{max}$ increases up to a certain limit beyond which further elevation in light level results in a decrease in light harvesting efficiency and photosynthetic capacity, and a loss of chlorophyll. That is because when the rate of light absorption exceeds the capacity for electron transport, the efficiency of light collection is "down-regulated" to prevent over-reduction of photosystem II. Although this down-regulation offsets longer term photoinhibitory effects, significant losses of photosynthesis occur during these processes. Under more severe conditions (temporary stresses such as extremely high light level, temperature extremes, and water deficit), down-regulation can be very long-lived, and even overloaded, resulting in photodamage. Preliminary studies indicate that alternative dissipative electron transfer pathways, such as the xanthophyll cycle, and free radical-scavenger enzymes like superoxide dismutase, catalase, and ascorbate peroxidase give plants overall tolerance for photo-oxidative stresses. The capacity of photoprotection is variable between species (Johnson et al 1993, Ruban et al 1993). Tu et al (1995) reported genotypic variation in photoinhibition and midday photosynthetic depression under high light-induced conditions, suggesting scope for improvement by breeding.

Increasing photosynthetic duration is often achieved by delaying the senescence of the flag leaf. Senescence is associated with the degradation of rubisco and chlorophyll. Rubisco breakdown usually occurs earlier than chlorophyll loss in a senescing leaf (Makino et al 1983). Increased late-season N application protects rubisco from degradation, which delays flag leaf senescence and increases photosynthetic duration. But delaying senescence of the flag leaf does not always result in greater yield if the sink is limiting. Moreover, delaying senescence of the flag leaf results in a reduction in nutrient translocation from the flag leaf to grain. The effects of the reduction in remobilization of nutrients from flag leaves on grain yield remain to be determined.

## Sink size

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 yield of 15 t ha$^{-1}$ with a 1,000-grain weight of 25 g.

Sink size is determined by spikelet number panicle$^{-1}$ and panicle number m$^{-2}$. Because a strong compensation mechanism exists between the two yield components, an increase in one component will 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 m$^{-2}$ is maintained. The way to delink the strong negative relationship between the two components is to increase biomass production during the critical phases of development when sink size is determined. Slafer et al (1996) stated 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 d before flowering in wheat (Fischer 1985). In rice, spikelet number m$^{-2}$, was highly related to DM accumulation in the period from panicle initiation to flowering (Kropff et al 1994). High light intensity and $CO_2$ enrichment enhanced the number of differentiated spikelets (Yoshida and Parao 1976). Wada and Matsushima (1962) also reported that spikelet formation is strongly affected by both N uptake and availability of carbohydrates from panicle initiation to flowering. Akita (1989) stated that there is 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 the period of 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 affecting the rate of development. 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 because of the fast development rate caused by high temperature or shortage in N uptake. Yoshida (1973) proved that the number of spikelets panicle$^{-1}$ 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 the competing sinks. This reduction could be achieved by reducing the length of the peduncle (the internode between the uppermost leaf node and the panicle) and reducing the number of unproductive tillers.

## Grain filling

Grain filling has a larger influence on yield potential as sink size increases. Spikelets can be fully filled, partially filled, or empty. Because grain size is rigidly controlled by hull size, the weight of a fully filled spikelet is relatively constant for a given variety (Yoshida 1981). Breeders rarely select for grain weight because of the negative linkage between grain weight and grain number. This does not mean that there is no opportunity to increase rice yield potential by selecting for heavy grains. But the major efforts should be directed toward 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, filled spikelet percentage, 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 ADP glucose pyro-phosphorylase (Stark et al 1992). Plant hormones, such as cytokinins, which 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 or delayed leaf senescence (Singh et al 1984). The capacity to transport assimilates from source to sink could also limit grain filling (Ashraf et al 1994). Indica rice has more vascular bundles in the peduncle relative to the number of primary branches of a panicle than japonica rice (Huang 1988). It is not clear whether the number of vascular bundles is more important than their size in terms of assimilate transporting.

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 monitored in this study. It is unknown whether 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 al (1996) proposed to increase grain-filling duration by manipulating responses to temperature. Hunt et al (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. High-density grains tended to occur on the primary branches of the panicle, whereas the spikelets of the secondary branches had low grain weight (Ahn 1986). Padmaja Rao (1987) reported that the top of the panicle (superior spikelet positions) has more high-density grains than the lower portion of the panicle (inferior spikelet positions). Varietal differences in number of high-density grains $panicle^{-1}$ were reported, and this trait appeared to be heritable (Venkateswarlu et al 1986).

It was suggested that 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 al 1986). But source limitation and regulation of assimilate allocation within the panicle make this difficult to achieve. Iwasaki et al (1992) found that superior spikelets are the first to accumulate DM and N during grain filling, whereas inferior spikelets do not begin to fill until DM accumulation in superior spikelets is nearly finished. This apical dominance within the panicle was immediately altered upon the removal of superior spikelets. It is unknown whether 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 al 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). The magnitude of damage from lodging depends on the degree of lodging and when lodging occurs. Lodging results from the interaction and balance of three forces: straw strength, environmental factors that affect straw strength, and the effect of external forces such as wind and rain (Setter et al 1994). Excessive N supply, deficiencies of K, Si, and Ca, low solar radiation, and diseases affecting the leaves, sheaths, and culm reduce straw strength (Chang and Loresto 1985). 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 when lodging occurs. Until internode elongation starts, the leaf sheaths support the whole plant. Even after the completion of internode elongation, the 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 al 1994). Ookawa and Ishihara (1992) reported that the breaking strength of the basal internode was doubled because of leaf sheath covering and was tripled because of the large area of the basal internode cross-section.

Terashima et al (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 the stem height of present semidwarf varieties are not a good approach for increasing lodging resistance because this will cause a reduction in biomass production. Lowering the height of the panicle could have a profound effect on increasing lodging tolerance because the height of the center of gravity of the shoot is reduced (Setter et al 1995). Ookawa et al (1993) studied the composition of the 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 the new plant type

Past success in increasing yield potential has mainly been the result of an empirical selection approach, that is, selecting 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 al 1996). Donald (1968) proposed the ideotype approach to plant breeding. In this approach, a plant type that is theoretically efficient based on knowledge of physiology and morphology is defined first. Breeders then select directly for the ideotype, rather than select only for yield. The ideotype concept initially emphasized morphological traits that are desirable for light interception and assimilate partitioning and then extended into the biochemical level (Hamblin 1993). It is expected that during the next few decades genetic improvement of yield potential will be accelerated using physiological attributes as selection criteria (Shorter et al 1991).

Semidwarf rice produces a large number of unproductive tillers and excessive leaf area that 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 al 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 al 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 panicle$^{-1}$, (4) very sturdy stems, (5) dark green, thick, and erect leaves, (6) vigorous root system, and (7) increased HI. Peng et al (1994) reviewed these individual traits in relation to yield potential, but 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). The breeding effort to develop this germplasm became a major core research project of the 1990-94 work plan (IRRI 1989b) and continued into the 1994-98 medium-term plan (IRRI 1993a). The goal was to develop a new plant type (NPT) with higher yield potential than the existing semidwarf varieties in tropical environments. Breeding work on the NPT began in 1989 when about 2,000 entries from the IRRI Genetic Resources Center were grown during the dry (DS) and wet seasons (WS) to identify donors for various traits (Khush 1995). Donors for low tillering, 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 the 1990 DS and $F_1$ progenies were grown for the first time in the 1990 WS, $F_2$ progenies in the 1991 DS, and a pedigree nursery in the 1991 WS. Since then, more than 1,800 crosses have been made, and 80,000 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 the 1993 WS. Their morphophysiological traits and yield potential have been evaluated since the 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. NPT lines have been bred from tropical japonicas within less than 5 yr. The NPT lines tested did not yield well because of poor grain filling. But 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. Selection pressure for good grain filling will be applied in the early generations. Research work on the NPT will be continued with the goals of breaking the yield barrier and increasing germplasm diversification.
2. Among the tested NPT lines, IR65598-112-2 consistently performed better than the others. The sink size of IR65598-112-2 is 10–15% higher than that of indica inbred checks. Its large panicles and other morphological traits resembled the ideotype proposed in 1989 by IRRI scientists, and its performance indicates 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, because low growth rate was observed between panicle initiation and flowering as well as during the ripening phase.
4. Nitrogen concentration and photosynthetic rate on a single-leaf level of the NPT lines showed no disadvantage compared with those of semidwarf indica varieties. The lower canopy photosynthetic rate and biomass production might be largely attributed to less tillering. A slight increase in the tillering capacity of the NPT should be considered.
5. Early flag leaf senescence can cause poor grain filling and large sink size can cause early leaf senescence as well. Early flag leaf senescence can be overcome by N application at flowering. Selection for long panicles while maintaining a large sink size may partially improve the grain filling of NPT lines.
6. Tillering synchrony of NPT lines needs to be improved because late tillers could contribute to poor grain filling.
7. Panicle size (i.e., spikelets panicle$^{-1}$) decreased more in NPT lines than in semidwarf indica varieties when panicle number increased. This result partially explains why the NPT lines did not perform better under direct seeding compared with transplanting.

8. We should also compare the efficiency of C and N remobilization from storage to grain between NPT lines and other varieties. Presently, we cannot rule out the possibility that assimilate transport is limiting in NPT lines.
9. Resistance to tungro and brown planthopper (BPH) must be incorporated into the NPT lines. We also need to improve grain quality. Donors for these traits have been identified and are being used in the hybridization program.
10. Hybridization between the NPT lines and indica inbreds is in progress. The intermediate lines between tropical japonicas and indicas could overcome some problems of the NPT lines. In the meantime, some NPT lines will be kept with a pure japonica background for developing indica/japonica $F_1$ hybrid rice.
11. Another strategy is to cross NPT lines with some cultivars from Texas (USA). Because these cultivars are intermediate between japonicas and indicas, they may not have problems of sterility and barriers to recombination. We hope that some good traits of the Texas cultivars, such as high grain-filling percentage, can be transferred into the NPT lines.

## Hybrid rice

More than 50% of China's rice area is now planted to rice hybrids. $F_1$ hybrid rice on the average has a yield advantage of about 15% over the best inbred varieties (Yuan 1994). These hybrids were evaluated in tropical countries and found to be susceptible to diseases and insects and not adapted (Virmani et al 1982). In 1978, IRRI began hybrid rice research to develop hybrids for tropical countries (Khush 1995). In the past 5 yr, some hybrid combinations developed at IRRI have shown a higher yield potential than the best indica inbred checks under tropical conditions. A few of these hybrids have been released for commercial production in tropical countries (Virmani 1994).

The yield potential of elite tropical hybrid IR68284H was compared with that of IR72 at IRRI and at the Philippine Rice Research Institute (PhilRice) in the 1995 DS. The hybrid produced 10.8 t $ha^{-1}$ at IRRI and 10.4 t $ha^{-1}$ at PhilRice, whereas IR72 yielded 7.7 t $ha^{-1}$ at IRRI and 9.9 t $ha^{-1}$ at PhilRice (Peng et al, unpublished data). The higher yield of the hybrid was attributed to more spikelets $m^{-2}$ at IRRI and to higher 1,000-grain weight at IRRI and PhilRice compared with IR72 (26.3 vs 21.3 g). Total DM at harvest of the hybrid was 10–17% higher than that of IR72. At PhilRice, the hybrid produced 23.5 t $ha^{-1}$ of DM, which was the highest biomass production reported for tropical rice. The most important trait of this hybrid is its stable and high grain-filling percentage compared with other tropical hybrids: 83% at IRRI and 79% at PhilRice, which was equivalent to that of IR72. High grain yield and grain-filling percentage were also observed in the 1994 DS from this hybrid. In the 1996 DS at PhilRice, IR68284H recorded the highest yield at 11.2 t $ha^{-1}$ and IR72 produced 10.6 t $ha^{-1}$. IR68284H may not have reached its genetic potential yet because 23% of the total spikelets were partially filled or empty and HI did not surpass 0.5. Virmani (1994) reported that the yield advantage of the hybrid IR64616H was higher in the high-yielding environment than in the low-yielding environment. We observed, however, that the heterosis reported from farmers' fields is usually higher than that from experiment-station fields. We believe that heterosis is generally higher at moderate yields than at high and low yields, but the underlying mechanism of this phenomenon is not known.

Almost all rice hybrids grown in China and those developed at IRRI have been crosses between indica varieties (Khush 1995). The magnitude of heterosis depends on the genetic diversity between the two parents. The greater the genetic difference between the parents, the higher the heterosis. During the past 30 yr, genetic diversity among improved indica rices has narrowed because of the massive international exchange of germplasm (Khush and Aquino 1994). Indica and japonica germplasms, however, have remained distinct as there has been little gene flow between these two groups. As expected, hybrids between indica and japonica varieties showed higher heterosis for yield than did indica/indica hybrids (Yuan et al 1989). The NPT development program was based on tropical japonica germplasm so that this improved germplasm would also be used for producing hybrids with higher heterosis. Hybrids between indica varieties and the NPT tropical japonicas are being evaluated at IRRI in small plots, and a higher level of heterosis in the indica/tropical japonica hybrid than in indica/indica hybrids was observed (Virmani, personal communication).

The increased yield of tropical rice hybrids is brought about by increased total biomass, higher spikelet number, and, to some extent, higher 1,000-grain weight (Ponnuthurai et al 1984). But the physiological basis of heterosis is still unknown. Single-leaf photosynthesis was measured in several studies to investigate the physiological basis of hybrid vigor, but the results were not consistent (Akita 1988). The single-leaf photosynthetic rates of IR64616H and IR72 were measured in the 1993 and 1994 DS. Tropical hybrids did not show a higher single-leaf photosynthetic rate than indica inbreds in the entire growing season. In fact, the hybrids had a slightly lower single-leaf photosynthetic rate during the rapid growing period and ripening phase because of their lower leaf N concentration compared with the inbreds (Peng et al, unpublished data). Sinclair and Hone (1989) compared leaf N concentration, single-leaf photosynthetic rate, LAI, and crop biomass production among rice, soybean, and maize. They argued that crop species with a lower N content but equivalent total leaf N will have a greater LAI and biomass accumulation because of higher canopy photosynthesis. The leaf N content of the hybrid is lower than that of IR72 when grown at the same N supply level, and this might be associated with heterosis in growth and grain yield.

## Improving yields in less favorable environments

Among rice-growing environments, rainfed lowland, upland, deepwater, and tidal wetland ecosystems are considered less favorable than irrigated ones (IRRI 1984). Nevertheless, these rainfed ecosystems constitute 45% of the total rice-growing area in Asia. Yield and production in these areas are only a fraction of the potential of improved rice. Average yield as low as 2 t ha$^{-1}$ is attributed to water- and soil-related factors. Scobie et al (1993) estimated that at least 30% of the projected 70% increase in global rice demand by the year 2030 must come from the rainfed lands. This estimate translates into a 100% yield increase in the rainfed lands of Asia, from 2 to 4 t ha$^{-1}$. This increase is also essential to release pressure on favorable environments (irrigated rice) that are prone to sustainability problems.

Soils over much of the Asian region, particularly in South Asia where the majority of rainfed rice is grown, are fertile and could support greater productivity. All rainfed ecosystems do not have the potential of yielding 4 t ha$^{-1}$. Moreover, improved cultivars alone cannot increase yield; improved management practices are also needed. Based on the yield-limiting factors, we can estimate the production potential of each ecosystem and the expected contribution from germplasm improvement and management technologies to achieve this potential (Table 1). An important assumption in these estimates is that the area remains unchanged, although the use of unfavorable uplands will likely be substantially reduced in the future. Large increases in tidal rice are expected in Indonesia and Vietnam. Nevertheless, we included a 10% safety factor in the yield target for 2030. Achieving 90% of this target is adequate to meet expectations for rainfed rice.

Nearly one-third of rainfed lowland rice has favorable growing conditions similar to those for irrigated rice. The NPTs developed for irrigated lands could be grown in these lands to produce about 7 t ha$^{-1}$ of yield. Breeding and management research

**Table 1. Present area and yield of Asian rainfed rice, year 2030 targets, and contributions expected from breeding and crop management research to achieve targets.[a]**

| Ecosystem or subecosystem | Approx. area (million ha) | Present yield (t ha$^{-1}$) | Year 2030 target yield (t ha$^{-1}$) | Contribution (%) expected from: Breeding | Management |
|---|---|---|---|---|---|
| **Lowland** | 39 | 2.3 | 4.7 | 64 | 36 |
| Favorable | 12 | 3.2 | 7.0 | 50 | 50 |
| Drought-prone | 7 | 1.6 | 3.0 | 60 | 40 |
| Drought- and submergence-prone | 4 | 1.3 | 2.5 | 80 | 20 |
| Submergence-prone | 10 | 2.0 | 4.0 | 90 | 10 |
| Waterlogged | 6 | 2.5 | 5.0 | 40 | 60 |
| **Upland** | 11 | 1.1 | 2.2 | 46 | 54 |
| Favorable | 2 | 1.5 | 3.0 | 30 | 70 |
| Unfavorable | 9 | 1.0 | 2.0 | 50 | 50 |
| **Flood-prone** | 10 | 1.5 | 3.1 | 56 | 44 |
| Deepwater | 5 | 1.5 | 3.0 | 70 | 30 |
| Floating | 1 | 0.7 | 2.0 | 10 | 90 |
| Tidal nonsaline | 1 | 2.2 | 5.0 | 80 | 20 |
| Tidal saline | 3 | 1.5 | 3.0 | 40 | 60 |

[a] Estimated by D. Senadhira.

needed for this subecosystem are in equal proportion. The drought-prone rainfed lowlands should increase yield performance to about 3 t $ha^{-1}$. The contribution from breeding is expected to be higher than for the favorable rainfed lowlands. The lowest yield potential is in the drought- and submergence-prone rainfed lowlands; for these lands, a major contribution has to come from breeding. Areas subjected to only submergence could produce about 4 t $ha^{-1}$ with submergence-tolerant improved varieties and some fertilizer inputs. Waterlogged rainfed lowlands are usually very productive and obtaining a yield of 5 t $ha^{-1}$ will not be difficult.

About 2 million ha of upland rice lands in Asia grow under favorable conditions. With appropriate management practices, especially those related to weed control, their yield could be raised to 3 t $ha^{-1}$. The yield potential of unfavorable uplands is low. Improved varieties with tolerance for drought and blast disease and weed management technologies are needed to increase the yield to 2 t $ha^{-1}$. In deepwater and floating-rice areas, soil and water management is impossible. Most of these lands, however, are fertile and increasing the yield of deepwater rice to 3 t $ha^{-1}$ with improved cultivars is a distinct possibility. Genetic improvement of floating rice is not worth pursuing. Biotechnological approaches (described later) hold some promise but better crop stand establishment and weed management could improve yield to about 2 t $ha^{-1}$. Tidal wetlands without major soil problems (salinity and acidity) have high yield potential because these lands are very fertile and pests and diseases are minimal. Their yield could easily be raised to 5 t $ha^{-1}$ with improved varieties. The lands affected by salinity and acidity require suitable soil and water management techniques plus cultivars with tolerance for these stresses.

Farmers in rainfed areas of Asia will continue to grow rice in the monsoon season but their increased input for high yields will depend on technologies that minimize risks derived from water- and soil-related stresses that occur on their lands. Some degree of tolerance for these stresses is available in the rice germplasm. Appropriate combinations that will match the needs of the many different niches of the rainfed systems are required to minimize risks. Limited knowledge of these traits—especially their physiological mechanisms, biochemical interactions, and inheritance—and lack of effective screening techniques hinder breeding progress.

Research investments so far have been on biotic stresses for protecting the yield gains achieved in irrigated rice. Investments in Bangladesh, India, and Thailand that addressed salinity, submergence, and waterlogging in rainfed rice have paid significant dividends. Data from India suggest that although resistance to pests and diseases per se contributed little to productivity, tolerance for abiotic stresses has contributed significantly to productivity increases (Evenson 1994). In the sections that follow, we discuss the present status of research on abiotic stresses. The vast amount of literature on cultivar variability and screening techniques for abiotic stresses will not be described or quoted. Instead, we will describe the future needs to attain the goal of breeding resistant cultivars. Abiotic stresses not discussed are not significant either for breeding or in the area affected.

## Water-related stresses

In the botanical sense, rice is not an aquatic plant, but it thrives in waterlogged soils where no other grain crop survives. It grows in lowlands without extensive drainage and flood protection devices. It can also be grown as a dryland crop in humid areas. Farmers grow rice on lands where water shortage is not expected, but erratic rainfall and floods cause problems of water deficit or excess. Drought, flash floods, and stagnant deepwater are the water-related stresses in rainfed rice systems.

*Drought.* Lack of water when needed is the most widespread constraint to higher rice yields. Simulated yields over 25 yr for the rainfed lowland condition in the Philippines revealed that, in the absence of drought stress, the yield potential of this environment can reach 6.5 t ha$^{-1}$ (Woperies et al 1993). Without built-in tolerance for drought, improvement in grain yields of drought-prone environments will be limited.

The physiological mechanisms of drought tolerance in rice are still poorly understood, probably because of its complexity resulting from timing, duration, and severity (Zeigler and Puckridge 1995). Research so far has been directed to the roots. Root number, thickness, depth, branching, regrowth capacity, and penetration capacity are believed to be the most important traits (O'Toole 1982). Although there is genetic variability for these traits and some knowledge of their genetics (Chang et al 1986), progress in developing drought-tolerant cultivars has been scant. The main reasons are (1) the traits are difficult to measure directly, (2) they are not very heritable (Ekanayake et al 1985), and (3) they contribute to drought avoidance only and not to true tolerance.

True drought tolerance or osmotic adjustment is found in rice and seems to offer some promise. In rice, osmosis begins quickly with the onset of moisture stress (Steponkus et al 1986, Turner et al 1986) and recent studies have shown that there are more variations for this trait in rice than previously thought (Fukai and Cooper 1994). A combination of drought-avoiding root traits with osmotic adjustment ability through breeding would produce genotypes with an adequate level of drought tolerance. The prerequisites are donors for the traits and rapid and reliable screening techniques.

*Flash flood submergence.* About 22 million ha of rainfed lowland and tidal wetland rice are prone to damage by flash floods. The crop is completely submerged, sometimes for 10–12 d and 2–3 times during the season. If the stress occurs during the early seedling stage, farmers can reseed the crop, but at later stages it is not possible because crops are rainfed. Delayed seeding results in water deficit during maturity. Submergence for more than 2–3 d kills ordinary rice. Some traditional cultivars, however, can survive complete submergence for 12–14 d.

The physiological mechanism of submergence tolerance is fairly well understood. Tolerant genotypes accumulate more starch and at a more rapid rate than sensitive genotypes and these reserves are used by alcoholic fermentation to produce energy and stay alive during submergence (Emes et al 1988). Methods of mass screening rice genotypes for tolerance have been developed. In the best tolerant cultivars, FR13A and Kurkaruppan, tolerance is governed by a single dominant gene (Mishra et al 1996). The existence of a different and recessive gene in cultivar Goda Heenati has been reported (Thach 1994). The availability of good screening techniques and knowledge of the genetics and physiological mechanisms have helped breeders in developing improved cultivars with good tolerance for submergence (Mackill et al 1993).

*Stagnant deepwater.* In more than 8 million ha of land in Asia, rice grows under rainfed lowland conditions for 1–3 mo, then is flooded to depths that exceed 50 cm (sometimes up to 4 m) for 1 mo or longer. Commonly called deepwater and floating (water depth exceeds 1 m) rice, it survives submergence by plant elongation (leaf sheath, leaf blade, and internodes) so that the leaf canopy is always kept above the water. As in submergence-tolerant cultivars, deepwater rice also accumulates starch before the floods arrive, but it is used for rapid growth when the crop is submerged. Floating rice elongates by as much as 15 cm $d^{-1}$ when submerged. The yield of elongating rice depends primarily on the maximum water depth and ranges from about 1 t $ha^{-1}$ in very deep areas to about 3 t $ha^{-1}$ in shallow (50–100 cm) areas. The physiological mechanisms and inheritance of elongation ability in deepwater rice are fairly well understood (Suge 1988). Screening methods for breeding and selection are available.

The potential for increasing the yield of elongating rice through genetic improvement exists only for areas with 1 m or less maximum water depth, approximately 5 million ha. In very deep areas where floating rice is grown, some increase is possible through good stand establishment and control of pests, weeds, and stem borers in particular. IRRI, in collaboration with the Rice Research Institute of Thailand, has developed an NPT for medium-deep areas taking into account need-based elongation and high-yielding leaf characteristics. The prototypes tested in Thailand significantly outyielded the local types (5 t $ha^{-1}$ versus 3.7 t $ha^{-1}$ for the local check) (IRRI 1995). Tests conducted at IRRI showed that the NPT could yield as high as the improved high-yielding varieties grown under irrigated conditions (Setter et al 1996).

## Soil-related stresses

On about 50 million ha of rice land in Asia, deficiency of phosphorus, zinc, or iron or excess of salts, iron, or aluminum limits rice yields. Some degree of varietal tolerance for these adverse factors has been clearly demonstrated. The potential for increasing yields of these lands, with a reasonable research input, is apparently great. The era of modifying the environment to fit the needs of current improved cultivars has passed. Adapting the plant to the natural environment should be the future approach to increasing and stabilizing rice yields. Improved cultivars that can tolerate stresses and are efficient in nutrient uptake and use are needed.

*Phosphorus deficiency.* Phosphorus deficiency occurs in acid and alkaline soils. These soils may have high soil P but low available P and they may also fix fertilizer P in highly insoluble forms. This stress is common in both lowland and upland rice.

Rice cultivars differ in their reaction to P deficiency. The physiological mechanism of tolerance for P deficiency in rice is still not known. Two types of mechanisms may account for the differences in tolerance: external efficiency, or the ability to extract insoluble P from the soil, and internal efficiency, or the ability to grow and reproduce normally with small amounts of P. The greenhouse screening technique used at IRRI with P-deficient nutrient solution detects internal efficiency, whereas the field technique that uses P-deficient (3 ppm available P) acid soil detects external efficiency. Some genotypes have shown tolerance in both tests, indicating the occurrence of both mechanisms in the same genotype. Neither technique is suitable for basic investigations and breeding. The greenhouse technique is confined to the seedling stage only, and, in the field technique, other stresses interact with the P problem. With respect to inheritance, Majumder et al (1989) reported high heterotic effects for P deficiency tolerance. Involvement of both additive and dominance gene effects, with moderate heritability and low environmental effects, have also been found (Chaubey et a1 1994). In both studies, phenotyping was done under naturally occurring acid soils and therefore findings could be related to external efficiency. Nevertheless, the inheritance of this trait is still not clear.

Breeding for P efficiency is not difficult if its inheritance is well understood and high-capacity screening techniques are available. Tolerance is common in traditional germplasm and screening data at IRRI show that it does not carry a yield cost, at least for internal P efficiency. Recent findings at IRRI suggest that a screening technique based on the ability to release P-chelating organic acid anions from the roots (for the uplands) (IRRI 1993b) and the ability of the roots to oxidize the reduced external medium (for the lowlands) (IRRI 1995) is worth exploring. Such a technique, when developed, will help us study the genetics of the trait and formulate selection procedures.

*Zinc deficiency.* Flooding decreases water-soluble zinc (Zn). As a result, Zn deficiency is the most common and widespread nutritional problem in lowland rice. Although Zn deficiency in the soil or rice plant can be corrected in many instances, incorporation of tolerance is more appropriate for rainfed lowland rice because of the lack of farmer resources. Furthermore, from 46 tests of 411 rice cultivars at 11 Zn-deficient sites, an average yield advantage of 3 t $ha^{-1}$ was obtained with tolerance (Neue et al 1990).

As with P deficiency, the physiological mechanisms and genetics of Zn deficiency tolerance are not known. Recent work at IRRI has shown the importance of root-induced changes in the rhizosphere in solubilizing Zn and increasing the plant's Zn uptake (Kirk and Bajita 1995). A measure of this root system's ability to oxidize a reducing environment could be a good indicator of uptake efficiency. Another research output is a solution culture technique that buffers solution pH at the required level despite nutrient uptake, supplies Zn at a realistic field solution level over time, and maintains adequate concentrations in solution of major nutrients during periods of rapid growth. The technique detects cultivars with a low Zn requirement and not those with root-induced solubilizing efficiency. IRRI will continue to work on these aspects, and methods for determining the genetics and selection criteria for Zn efficiency will soon be available.

*Iron deficiency.* Iron is rarely in short supply in the soil but, because of its insolubility under certain conditions, iron deficiency is a serious disorder in rice on neutral or alkaline aerobic (upland) soils. In the lowlands, it occurs in alkaline soils and, regardless of pH, in soils that dry out when the rains do not come. Because iron fertilization is costly and difficult, breeding for iron efficiency is an important goal. There is wide variability in rice for tolerance for iron deficiency. Traditional upland rice cultivars are less susceptible to iron deficiency than wetland varieties (IRRI 1977). Yield reduction caused by iron deficiency can be as high as 65% in sensitive varieties compared with zero or insignificant reduction in tolerant cultivars (IRRI 1979).

Other than limited germplasm screening, little research on iron deficiency is conducted probably because only upland breeders are concerned about it and because upland germplasm is generally adapted to iron-deficient soil conditions. In the future, however, when some lowland rice traits need to be transferred to upland rice to increase yield potential, iron deficiency tolerance will certainly become important. The role of iron during dry spells in the lowlands is not known, and we urgently need to intensify research on Fe deficiency tolerance in rice.

*Nitrogen deficiency.* After water, nitrogen (N) is the most important contributor to high yields. N deficiency is usually not considered a soil-related stress because it can be easily corrected by addition. But evidence suggests genetic variation in associative $N_2$ fixation, N acquisition, and conversion efficiency (Ladha et al 1995). Further exploration and exploitation of these traits will be useful to all rainfed rice systems because farmers are always reluctant to use high levels of N fertilizer.

*Salinity.* Because rice grows in water, rice is the best crop for saline and highly alkaline soils. Continuous rice culture reduces alkalinity. In Asia, four different types of salinity affect rice (Moormann and van Breemen 1978): (1) coastal salinity, (2) inland salinity-alkalinity by interflow, (3) groundwater salinity-alkalinity, and (4) surface water salinity-alkalinity. Rice in the first two types is usually rainfed and rice in the other two is grown with irrigation in arid and semiarid areas. Salinity is important to future rice production because of the extent of saline soils presently cultivated, and the suitability of about 9.5 million ha of land in South and Southeast Asia for cultivation with salt-tolerant rice cultivars (Boje-Klein 1986).

Salinity is the only soil-related stress with adequate information to back up breeding research. Physiological mechanisms are fairly well understood (Yeo et al 1990). Knowledge of inheritance is adequate (Moeljopawiro and Ikehashi 1981, Akbar et al 1985, Narayan et al 1990, Gregorio and Senadhira 1993), and good donors and screening techniques are available. There are, however, opportunities for refining the screening techniques and enhancing tolerance by pyramiding the different tolerance mechanisms.

*Iron toxicity.* About 4 million ha of rainfed lowland and flood-prone rice in Asia are affected by iron toxicity. It is usually associated with high acidity and low nutrient status, particularly of K or P. Among all soil-related stresses, iron toxicity is the most complex. The reported values for toxic level in soil solution range from 10 to 1,000 ppm (Tanaka et al 1966) because many other soil as well as climatic and plant factors influence iron toxicity (Cho and Ponnamperuma 1971). This complexity has resulted in the lack of specific criteria for stress evaluation and the lack of good screening techniques. But breeding cultivars tolerant of iron toxicity is promising because of a wide variability between cultivars (Neue 1991). Indonesia and Sri Lanka have developed and released several high-yielding cultivars with good levels of tolerance. Breeding iron toxicity-tolerant cultivars could be expedited if reliable screening techniques were developed and if its inheritance were thoroughly elucidated.

*Aluminum toxicity.* Aluminum toxicity occurs in acid uplands and lowlands with acid sulfate soil conditions. In the uplands, it is often associated with manganese toxicity. Aluminum toxicity results in poor root growth, leading to reduced nutrient and water uptake, which in turn increases the plant's sensitivity to drought. The relative root length method of screening is widely used and accepted because it can effectively screen large numbers of genotypes and the scores obtained correlate well with field performance and grain yield screening (Howeler and Cadavid 1976, Coronel et al 1990). The tolerance mechanism appears similar to that of salinity tolerance, in which exclusion capacity and lowered translocation to the shoot are found (Howeler and Cadavid 1976). The inheritance of tolerance is simple (Khatiwada 1995). The only breeding problem encountered is the laborious and cumbersome screening technique.

## Stress occurrence and interactions

Stresses rarely occur alone. Table 2 shows the major abiotic stresses of some sites in Asia, representing various rainfed rice systems. Each site has at least two stresses and some have as many as six. The long-term adaptability of a cultivar depends on its level of tolerance for all the stresses that occur in its growing environment. There could be seasons in which some stresses may not occur at all. For example, Al toxicity will not occur if there is sufficient rain to keep the soil saturated. On the other hand, stresses such as P deficiency will remain unchanged. Another variability is stress severity, which can occur over both time and space. Salinity is a good example in which the stress level in the soil varies because of high solubility and mobility of salts; it also varies depending on rainfall or water availability. These variations form a major constraint to breeding where segregating populations are evaluated in target environments for selection. Although the procedure is highly inefficient, there is no alternative. The available screening techniques are of limited capacity and do not permit simultaneous screening for several stresses.

Another constraint associated with field evaluation is the interaction between stresses that may mislead breeders. Drought-sensitive cultivars may express tolerance for drought because of their tolerance for Al. In such a situation, breeders are unable to distinguish between drought-tolerant and drought plus aluminum toxicity-tolerant cultivars. Current knowledge about interactions between soil-related stresses and water-related stresses is limited. Although the physiological mechanisms of flooding tolerance (submergence tolerance and elongation ability) are known, their function under different soil conditions is not. This is a major constraint to the breeding process.

**Table 2. Main abiotic stresses of some areas representing different subecosystems of the rainfed ecosystems (+ indicates presence of stress).**

| Stress | Rainfed lowland | | | | | Upland | | Flood-prone | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1a | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| Drought (vegetative) | | + | + | | | | + | + | + | | | |
| Drought (reproductive) | | + | + | + | | + | + | | | | + | |
| Flash flood submergence | | | + | + | + | | | | | + | + | + |
| Deep water (51 m) | | | | | | | | + | + | | | |
| Very deep water ($\geq$1 m) | | | | | | | | | + | | | |
| P deficiency | + | + | + | | + | + | + | + | + | + | | + |
| Zn deficiency | + | | | | | | | + | | | + | |
| Fe deficiency | | | | | | + | + | + | | | | |
| Salinity | | | + | | | | | | | | + | |
| Fe toxicity | | | | | | | | | + | | | + |
| Al toxicity | | | | | | | + | | + | | | + |
| Organic acids and H,S toxicity | | | | | | | | | | | | + |

[a]1 = Terai region, Nepal; 2 = Cuttack, India; 3 = Khon Kaen, Thailand: 4 = Lopez, Philippines: 5 = Gampaha, Sri Lanka; 6 = Claveria, Philippines; 7 = Sitiung, Indonesia, 8 = Pusa. India; 9 = Bangsang, Thailand: 10 = San Jose, Philippines; 11 = Castuli, Philippines; 12 = Unit Tatas, Indonesla.

## Role of biotechnology in rice yield improvement

Genetic engineering techniques offer new opportunities for accelerating breeding progress, increasing selection efficiency, and transferring genes across species and genetic barriers. The challenge for plant breeders is to capitalize on these novel techniques.

*Tissue culture.* Tissue culture allows somaclonal variation and in vitro selection, thereby shortening the breeding cycle. Somaclonal variation was used to overcome some difficult problems of breeding for salinity tolerance in rice (Senadhira et al 1994). Hagonoy, the salt-tolerant improved rice cultivar released in the Philippines, was produced by $F_1$ anther culture, a technique used extensively at IRRI in its NPT breeding program. Most rainfed rice grown in Asia is photoperiod-sensitive. Because it is cultivated only once a year, developing a new variety takes about 10 yr. This period could be reduced to 3–4 yr with anther culture.

*DNA probes.* With conventional techniques, breeders have to rely on the phenotypic expression of genes. Selection efficiency is substantially reduced by this expression when interactions occur. Furthermore, approaches such as gene pyramiding for enhanced adaptability are impossible to undertake with conventional methods. With molecular biology techniques, breeders can detect alleles of interest in their materials by using DNA probes and by chemical or immunological assays. These techniques have numerous advantages. The tests have unlimited capacity and are nondestructive, rapid, and reliable (as high as 100%). The biggest advantage is their ability to detect in one screening the presence or absence of any number of alleles of interest. Most of the problems described in earlier sections could be overcome by these marker-aided selection (MAS) techniques. A prerequisite to developing MAS techniques for a trait is precise phenotyping, which, in turn, demands an understanding of the physiological mechanism of the trait and its inheritance pattern. For drought and most soil-related stresses, these prerequisites are still lacking. Development of MAS techniques for tolerance of flooding and salinity is in progress at IRRI.

*Gene transformation.* Transformation will open new opportunities to solve old problems. One good example is the control of stem borer and sheath blight. There are no known sources of resistance to this insect and this disease and chemical control is costly and unacceptable. Transformation with genes producing insecticidal proteins such as endotoxins of *Bacillus thuringiensis* (*Bt*) and tripsin inhibitors should reduce stem borer damage. Similarly, the chitinase-producing gene can suppress the sheath blight pathogen. Floating-rice cultivars, when transformed with the *Bt* gene, could substantially increase the yields of very deeply flooded rice lands. Apomixis, if transferred to rice from other species, will revolutionize hybrid rice cultivation.

Biotechnology tools, especially MAS techniques, will certainly provide solutions to most problems associated with breeding improved rice with tolerance for abiotic stresses. We urgently need to intensify research on the genetics and physiological mechanisms of tolerance traits. Priority should be given to drought, P and Zn efficiency, and iron toxicity tolerance. Cooperation among breeders, geneticists, stress physiologists, plant nutritionists, and biotechnologists is vital to produce the rainfed rice cultivars that we need for the future.

## References


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

Akbar M, Khush GS, HilleRisLambers D. 1985. Genetics of salt tolerance in rice. In: Rice genetics. Manila (Philippines): International Rice Research Institute. p 399-409.

Akita S. 1988. Physiological bases of heterosis in rice. In: Hybrid rice. Manila (Philippines): International Rice Research Institute. p 67-77.

Akita S. 1989. Improving yield potential in tropical rice. In: Progress in irrigated rice research. Manila (Philippines): International Rice Research Institute. p 41-73.

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

Austin RB. 1993. Crop photosynthesis: can we improve on nature? In: International crop science I. Madison, Wis. (USA): Crop Science Society of America. p 697-701.

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.

Boje-Klein G. 1986. Problem soils as potential areas for adverse soil-tolerant rice varieties in South and Southeast Asia. IRRI Research Paper Series 119.

Chang TT, Armenta-Soto JL, Mao CX, Peins R, Loresto GC. 1986. Genetic studies on the components of drought resistance in rice (*Oryza sativa* L.). In: Rice genetics. Manila (Philippines): International Rice Research Institute. p 387-398.

Chang TT. 1964. Varietal differences in lodging resistance. Int. Rice Comm. Newsl. 13(4): 1-11.
Chang TT, Loresto GC. 1985. Lodging in rice. Rice Production and Extension, Management Specialist Training Course, September 1985. Manila (Philippines): International Rice Research Institute.
Chang TT, Vergara BS. 1972. Ecological and genetic information on adaptability and yielding ability in tropical varieties. In: Rice breeding. Manila (Philippines): International Rice Research Institute. p 431-453.
Chaubey CN, Senadhira D, Gregorio GB. 1994. Genetic analysis of tolerance for phosphorus deficiency in rice (*Oryza sativa* L.). Theor. Appl. Genet. 89:313-317.
Cho DY, Ponnamperuma FN. 1971. Influence of soil temperature on the chemical kinetics of flooded soils and the growth of rice. Soil Sci. 112(3):184-194.
Coronel P, Akita S, Yoshida S. 1990. Aluminum toxicity tolerance in rice (*Oryza sativa* L.) seedlings. In: van Bensichem, editor. Plant nutrition: physiology and applications. Kluwer Academic Publishers.
Dai Q, Peng S, Chavez AQ, Vergara BS. 1995. Effects of UVB radiation on stomatal density and opening in rice (*Oryza sativa* L.). Ann. Bot. 76:65-70.
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. Manila (Philippines): International Rice Research Institute. p 17-38.
Donald CM. 1968. The breeding of crop ideotypes. Euphytica 17:385-403.
Ekanayake IJ, Garrity DP, Masajo TM, O'Toole JC. 1985. Root pulling resistance in rice: inheritance and association with drought tolerance. Euphytica 34:905-913.
Elmore CD. 1980. The paradox of no correlation between leaf photosynthetic rates and crop yields. In: Hesketh JD, Jones JW, editors. Predicting photosynthesis for ecosystem models. Vol. II. Boca Raton (Fla., USA): CRC Press. p 155-167.
Emes MJ, Wilkin CP, Smith P, Kupkanchanakul K, Hawker K, Charlton WA, Cutter EG. 1988. Starch utilization by deepwater rice during submergence. In: The 1987 international deepwater rice workshop. Manila (Philippines): International Rice Research Institute.
Evans LT. 1990. Raising the ceiling to yield: the key role of synergisms between agronomy and plant breeding. In: Muralidharan K, Siddiq EA, editors. New frontiers in rice research. Hyderabad (India): Directorate of Rice Research. p 103-107.
Evenson RE. 1994. Varietal yield and trait value estimates: rice in India. In: Proceedings of the international workshop on rice research prioritization. Manila (Philippines) and New York (USA): International Rice Research Institute and Rockefeller Foundation.
Fischer RA. 1985. Number of kernels in wheat crops and the influence of solar radiation and temperature. J. Agric. Sci. 100:447-461.
Fischer RA. 1994. Key issues in wheat yield potential. In: Cassman KG, editor. Breaking the yield barrier. Manila (Philippines): International Rice Research Institute.
Fukai S, Cooper M. 1994. Stress physiology in relation to breeding for drought tolerance: a case study of rice. In: Rainfed lowland rice: physiology of stress tolerance. Manila (Philippines): International Rice Research Institute.
Gent MPN. 1995. Canopy light interception, gas exchange, and biomass in reduced height isolines of winter wheat. Crop Sci. 35:1636-1642.
Gifford RM, Thorne JH, Hitz WD, Gianquinta RT. 1984. Crop productivity and photoassimilate partitioning. Science 225:801-808.

Gregorio GB, Senadhira D. 1993. Genetic analysis of salinity tolerance in rice (*Oryza sativa* L.). Theor. Appl. Genet. 86:333-338.
Hamblin J. 1993. The ideotype concept: useful or outdated? In: International crop science I. Madison, Wis. (USA): Crop Science Society of America.
Hitaka H. 1969. Studies on the lodging of rice plants. Jpn. Agric. Res. Q. 4(3):1-6.
Horton P, Ruban AV. 1992. Regulation of photosystem II. Photosynth. Res. 34:375-385.
Howeler RH, Cadavid F. 1976. Screening of rice cultivars for tolerance to Al toxicity in nutrient solution as compared with field screening method. Agron. J. 68:551-555.
Huang H. 1988. Japonica and indica differences in large vascular bundles in culm. Int. Rice Res. Newsl. l3(1):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 (International Rice Research Institute). 1977. Annual report for 1976. Manila (Philippines): IRRI. 418 p.
IRRI (International Rice Research Institute). 1979. Annual report for 1978. Manila (Philippines): IRRI. 478 p.
IRRI (International Rice Research Institute). 1984. Terminology for rice-growing environments. Manila (Philippines): IRRI. 35 p.
IRRI (International Rice Research Institute). 1989a. IRRI toward 2000 and beyond. Manila (Philippines): IRRI.
IRRI (International Rice Research Institute). 1989b. Implementing the strategy: work plan for 1990-1994. Manila (Philippines): IRRI. p 15-17.
IRRI (International Rice Research Institute). 1993a. Rice research in a time of change: IRRI's medium-term plan for 1994-1998. Manila (Philippines): IRRI. p 35-36.
IRRI (International Rice Research Institute). 1993b. Program report for 1992. Manila (Philippines): IRRI. 316 p.
IRRI (International Rice Research Institute). 1995. Program report for 1994. Manila (Philippines): IRRI. 311 p.
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(3):517-525.
Janoria MP. 1989. A basic plant ideotype for rice. Int. Rice Res. Newsl. 14(3): 12-13.
Johnson GN, Young AJ, Scholes JD, Horton P. 1993. The dissipation of excess excitation energy in British plant species. Plant Cell Environ. 16:673-679.
Khatiwada SP. 1995. Variability and genetics of tolerance for aluminum toxicity in rice (*Oryza sativa* L.). MS thesis. University of the Philippines Los Baños, Laguna, Philippines. 58 p.
Khush GS. 1995. Breaking the yield frontier of rice. GeoJournal 35(3):329-332.
Khush GS, Aquino R. 1994. Breeding tropical japonicas for hybrid rice production. In: Virmani SS, editor. Hybrid rice technology: new developments and future prospects. Manila (Philippines): International Rice Research Institute.
Khush GS, Peng S. 1996. Breaking the yield frontier of rice. In: Reynolds MP, Rajaram S, McNab A, editors. Increasing yield potential in wheat: breaking the barriers. Mexico: International Maize and Wheat Improvement Center. p 36-51.
Kirk GJD, Bajita JB. 1995. Root-induced iron oxidation, pH changes and zinc solubilization in the rhizosphere of lowland rice. New Phytol. 131:129-137.

Kishore GM. 1994. Starch biosynthesis in plants: identification of ADP glucose pyrophosphorylase as a rate-limiting step. In: Cassman KG, editor. Breaking the yield barrier. Manila (Philippines): International Rice Research Institute. p 117-119.

Kropff MJ, Cassman KG, Peng S, Matthews RB, Setter TL. 1994. Quantitative understanding of yield potential. In: Cassman KG, editor. Breaking the yield barrier. Manila (Philippines): International Rice Research Institute. 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(3):374-382.

Ladha JK, Kirk GJD, Peng S, Reddy K, Reddy PM, Singh U, Bennett J. 1995. Opportunities for increased nitrogen use efficiency from improved rice germplasm in lowland rice ecosystems. Paper presented at the Workshop on Nutrient Use Efficiency of the Cropping Systems, 13-15 Dec 1995, International Rice Research Institute, Los Baños, Philippines.

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

Mackill DJ, Amante MM, Vergara BS, Sarkarung S. 1993. Improved semidwarf rice lines with tolerance to submergence of seedlings. Crop Sci. 33:749-753.

Majumder ND, Borthakur DN, Rakshit SC. 1989. Heterosis in rice under phosphorous stress. Indian J. Genet. 49:231-235.

Makino A, Mae T, Ohira K. 1983. Photosynthesis and ribulose-1,5-bisphosphate carboxylase in rice leaves. Plant Physiol. 73:1002-1007.

Makino A, Mae T, Ohira K. 1984. Relation between nitrogen and ribulose-1,5-bisphosphate carboxylase in rice leaves from emergence through senescence. Plant Cell Physiol. 25(3):429-437.

Mazaredo AM, Laureles EV, Setter TL. 1996. Growth and yield of modern deepwater rice: comparisons with modern irrigated rice. Field Crops Res. 46:105-116.

McDonald DJ, Stansel JW, Gilmore EC. 1974. Breeding for high photosynthetic rate in rice. Indian J. Genet. 34A:1067-1073.

Mishra SB, Senadhira D, Manigbas NL. 1996. Genetics of submergence tolerance in rice (*Oryza sativa* L.). Field Crops Res. 46:177-181.

Moeljopawiro S, Ikehashi H. 1981. Inheritance of salt tolerance in rice. Euphytica 30:291-300.

Moormann FR, van Breemen N. 1978. Rice: soil, water, land. Manila (Philippines): International Rice Research Institute. 185 p.

Murata Y. 1961. Studies on the photosynthesis of rice plants and its cultural significance. Bull. Natl. Inst. Agric. Sci. Jpn. Ser. D, 9:1-169.

Narayan KK, Krishnaraj S, Sree Rangaswamy SR. 1990. Genetic analysis for salt tolerance in rice. In: Rice genetics II. Manila (Philippines): International Rice Research Institute. p 167-173.

Neales TF, Incoll LD. 1968. The control of leaf photosynthesis by the level of assimilate concentration in the leaf: a review of the hypothesis. Bot. Rev. 34:107-125.

Nelson CJ. 1988. Genetic associations between photosynthetic characteristics and yield: review of the evidence. Plant Physiol. Biochem. 26:543-554.

Neue HU. 1991. Adverse soil tolerance of rice: mechanisms and screening techniques. In: Deturk P, Ponnamperuma FN, editors. Rice production on acid soils in the tropics. Kandy (Sri Lanka): Institute of Fundamental Studies. p 243-250.

Neue HU, Lantin RS, Cayton MTC, Autor NU. 1990. Screening of rices for adverse soils tolerance. In: El Bassam N, Dambroth M, Loughman BC, editors. Genetic aspects of plant nutrition. Kluwer Academic Publishers.

O'Toole JC. 1982. Adaptation of rice to drought-prone environments. In: Drought resistance in crops with emphasis on rice. Manila (Philippines): International Rice Research Institute. p 195-213.

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(4):525-533.

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(3):419-425.

Padmaja Rao S. 1987. Panicle type: few structural considerations for higher yield potential in rice. Indian J. Plant Physiol. 30(1):87-90.

Peng S, Cassman KG. 1998. Upper thresholds of nitrogen uptake rates and associated nitrogen fertilizer efficiencies in irrigated rice. Agron. J. (accepted).

Peng S, Cassman KG, Kropff MJ. 1995. Relationship between leaf photosynthesis and nitrogen content of field-grown rice in the tropics. Crop Sci. 35:1627-1630.

Peng S, Khush GS, Cassman KG. 1994. Evolution of the new plant ideotype for increased yield potential. In: Cassman KG, editor. Breaking the yield barrier. Manila (Philippines): International Rice Research Institute. p 5-20.

Penning de Vries FWT. 1991. Improving yields: designing and testing VHYVs. In: Systems simulation at IRRI. IRRI Research Paper Series 5. Manila (Philippines): International Rice Research Institute. p 13-19.

Ponnuthurai S, Virmani SS, Vergara BS. 1984. Comparative studies on the growth and grain yield of some $F_1$ rice (*Oryza sativa* L.) hybrids. Philipp. J. Crop Sci. 9(3):183-193.

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

Richards RA. 1996. Increasing yield potential: source and sink strength. In: Reynolds MP, Rajaram S, McNab A, editors. Increasing yield potential in wheat: breaking the barriers. Mexico: International Maize and Wheat Improvement Center. p 134-149.

Ruban AV, Young AJ, Horton P. 1993. Induction of nonphotochemical energy dissipation and absorbance changes in leaves. Plant Physiol. 102:741-750.

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

Scobie BM, McDonald D, Willey R. 1993. Investment in rice research in the CGIAR: a global perspective. Rome (Italy): TAC Secretariat, FAO.

Senadhira D, Li GF. 1989. Variability in rice grain-filling duration. Int. Rice Res. Newsl. 14(1): 8-9.

Senadhira D, Neue HU, Akbar M. 1994. Development of improved donors for salinity tolerance in rice through somaclonal variation. SABRAO J. 26(1-2):19-25.

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. Austr. 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: Cassman KG, editor. Breaking the yield barrier. Manila (Philippines): International Rice Research Institute. p 39-62.

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

Sinclair TR, Horie T. 1989. Leaf nitrogen, photosynthesis, and crop radiation use efficiency: a review. Crop Sci. 29:90-98.

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. Generation of yield components and compensation in wheat: opportunities for further increasing yield potential. In: Reynolds MP, Rajaram S, McNab A, editors. Increasing yield potential in wheat: breaking the barriers. 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 re-examination of some assumptions made by physiologists and modellers. Austr. 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.
Steponkus PL, Shahan KW, Cutler JM. 1986. Osmotic adjustment in rice. In: Drought resistance in crops with emphasis on rice. Manila (Philippines): International Rice Research Institute. p 181-194.
Suge H. 1988. Physiological genetics of internode elongation in submerged deepwater rice. In: Proceedings of the 1987 International Deepwater Rice Workshop. Manila (Philippines): International Rice Research Institute. p 275-286.
Tanaka A, Los R, Navasero SA. 1966. Some mechanisms involved in the development of iron toxicity symptoms in the rice plant. Soil Sci. Plant Nutr. 12:32-38.
Teare ID, Peterson CJ, Law AG. 1971. Size and frequency of leaf stomata in cultivars of *Triticum aestivum* and other *Triticum* species. Crop Sci. 11:496-498.
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.
Thach TD. 1994. The genetic association between elongation ability and submergence tolerance in rice. MS thesis. Central Luzon State University, Muñoz, Nueva Ecija, Philippines. 65 p.
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.
Tu ZP, Lin XZ, Cai WJ, Yu ZY. 1995. Reprobing into rice breeding for high photosynthetic efficiency. Acta Bot. Sin. 37(8):641-651.
Turner NC, O'Toole JC, Cruz RT, Yambao EB, Ahmed S, Namuco OS, Dingkhun M. 1986. Response of seven diverse rice cultivars to water deficits. 2. Osmotic adjustment, leaf elasticity, leaf extension, leaf death, stomatal conductance and photosynthesis. Field Crops Res. 13:273-286.
Venkateswarlu B, Vergara BS, Parao FT, Visperas RM. 1986. 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.
Virmanj SS. 1994. Prospects of hybrid rice in the tropics and subtropics. In: Virmani SS, editor. Hybrid rice technology: new developments and future prospects. Manila (Philippines): International Rice Research Institute. p 7-19.
Virmani SS, Aquino RC, Khush GS. 1982. Heterosis breeding in rice, *Oryza sativa* L. Theor. Appl. Genet. 63:373-380.
Wada G, Matsushima S. 1962. Analysis of yield determining processes and its application to yield prediction and culture improvement of lowland rice. Proc. Crop Sci. Soc. Jpn. 31:15-18.

Woperies MCS, Kropff MJ, Hunt ED, Sanidad W, Bouman J. 1993. Case study on regional application of crop growth simulation models to predict rainfed rice yields, Tarlac Province, Philippines. In: Bouman BAM, van Laar HH, Zhaoqian W, editors. Proceedings of an international workshop on agroecological zonation of rice. Wageningen Agricultural University.

Yeo AR, Yeo ME, Flowers SA, Flowers TH. 1990. Screening of rice (*Oryza sativa* L.) genotypes for physiological characters contributing to salinity resistance and their relationship to overall performance. Theor. Appl. Genet. 79:377-384.

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

Yoshida S. 1981. Fundamentals of rice crop sciences. Manila (Philippines): International Rice Research Institute.

Yoshida S, Coronel V. 1976. Nitrogen nutrition, leaf resistance, and leaf photosynthetic rate of the rice plant. Soil Sci. Plant Nutr. 22(2):207-211.

Yoshida S, Parao FT. 1976. Climatic influence on yield and yield components of lowland rice in the tropics. In: Climate and rice. Manila (Philippines): International Rice Research Institute. p 471-494.

Yuan LP, Virmani SS, Mao CX. 1989. Hybrid rice: achievements and future outlook. In: Progress in irrigated rice research. Manila (Philippines): International Rice Research Institute. p 219-223.

Yuan LP. 1994. Increasing yield potential in rice by exploitation of heterosis. In: Virmani SS, editor. Hybrid rice technology: new developments and future prospects. Manila (Philippines): International Rice Research Institute. p 1-6.

Zeigler RS, Puckridge DW. 1995. Improving sustainable productivity in rice-based rainfed lowland systems of South and Southeast Asia. GeoJournal 35(3):307-324.

Zelitch I. 1982. The close relationship between net photosynthesis and crop yield. Bioscience 32:796-802.

## Notes

*Authors' address;* S. Peng, International Rice Research Institute (IRRI), P.O. Box 933, Manila, Philippines. s.peng@cgnet.com; D. Senadhira is deceased.

*Citation:* Dowling NG, Greenfield SM, Fischer KS, editors. 1998. Sustainability of rice in the global food system. Davis, Calif. (USA): Pacific Basin Study Center, and Manila (Philippines): International Rice Research Institute.

CHAPTER 8

# Intensification of rice production systems: opportunities and limits

W. Reichardt, A. Dobermann, and T. George

Intensification of rice systems implies the disturbance of existing equilibria in soil by extensive submergence and elevated levels of agrochemicals in nutrient and pest management. In keeping pace with the deployment of ever higher yielding rice varieties, nutrient management risks adversely affecting the agronomic and environmental sustainability of rice lands. The first signs of declining productivity reported from on-station field experiments have been linked to reduced soil N-supplying capacity. Furthermore, neglect of non-N mineral fertilizers has frequently led to depletion in K, P, S, and Zn. In regions with rapidly progressing intensification, inputs of organic carbon as residue or as manure have been discontinued. On the other hand, the organic matter pool of rice-cropping systems can be seen as a mechanistic key to nutrient supply. With microbial biomass as its most rapidly recycled segment, the organic phase serves as a source of biocatalysts governing nutrient supply and as a nutrient pool by itself. The dynamics of the organic matter phase in flooded soils are fundamentally different from those in aerated soils. Green manure derived from N-fixing organisms has its merits in less intensified systems where it can provide sufficient N at N rates below 100 kg ha$^{-1}$. Options for sustaining the most intensified resource bases would have to include a demand-driven integrated inorganic/organic nutrient management and rotation cropping, the latter mainly in response to periodic annual shortages of irrigation water. As a prerequisite for the rotation of rice with upland crops, however, an efficient, fine-tuned nutrient and pest management would have to be established. In tropical wetlands, intensive rice cropping is dealing with a greater diversity of habitats and biological and biogeochemical functions over space and time than other agroecosystems. In accordance with ecological theory, this is likely to confer maximum stability and sustainability on agricultural wetlands.

## Intensification and its impact on the soil resource base

### Sustainability

About 30 years after the Green Revolution in Asia, the sustainability of intensified rice production systems can be viewed from different perspectives that reflect seemingly conflicting interests. The application of more recent concepts in agroeconomics, however, could bridge the gap between economic and ecological goals. Replacing the gross domestic product with the net domestic product has become a conceptual advance with far-reaching consequences. It requires agronomists to include impacts on environmental capital in agronomic yield equations (Swaminathan 1991).

It was remarkable that agronomists and not ecologists triggered the resurging interest in sustainable rice production. Following dramatic yield increases since the 1960s, productivity in farmers' fields in Southeast Asia became stagnant or even declined from the mid–1980s (Flinn and De Datta 1984, Cassman and Pingali 1995a, Cassman et al 1996). Given the expected increase in future demand for rice and plant breeders' capacity to develop varieties for higher and more stable yields, the limiting capacity of the soil resource base has become a crucial issue. Opportunities to enhance yield through improved nutrient, water, and pest management will have to be balanced against the hidden risk of degrading the agronomic and environmental quality of rice-growing areas and beyond.

## Rice cropping before the Green Revolution

Wetland rice is the only major crop that was grown for many centuries and possibly millennia in monoculture without major soil degradation (Bray 1986, Uexkuell and Beaton 1992). Soil flooding and puddling maintained favorable soil properties for rice growth (Ponnamperuma 1972), and traditional rice-growing patterns were geared for stability instead of high yields. Traditional long-duration varieties (130–210 d) with low harvest index and yield were grown and, in many areas, much of the straw remained in the field (Uexkuell and Beaton 1992). Bunds protected rice fields from soil erosion. Floodwater buffered the soil temperature and allowed ample growth of $N_2$-fixing microorganisms (Roger 1996). Suspended particles and soluble nutrients from rainfall and irrigation water contributed to an indigenous nutrient supply covering the demand of extensively grown crops. Current rainfall contributions to annual nutrient inputs to irrigated rice fields of Asia are estimated to be in the range of 1–10 kg N $ha^{-1}$, 0.2–2 kg P $ha^{-1}$, 3–10 kg K $ha^{-1}$, and 5–20 kg S $ha^{-1}$. Low net total nutrient inputs may have supported yields of 1–2 t $ha^{-1}$.

In traditional irrigated rice systems where net total nutrient removal as well as daily nutrient uptake rates were low, nutrient additions from natural sources were an important component of the overall nutrient balance, and even poor soils had the capacity to supply enough nutrients to sustain yields of 1–2 t $ha^{-1}$. Such systems originated in river valleys and deltas of Asia and they remained unchanged for hundreds of years.

## Intensification effects on physicochemical properties of flooded rice soils

The invention and widespread adoption of high-yielding, early maturing semidwarf indica varieties in the 1960s led to a rapid intensification in the tropical lowlands of Asia. New varieties such as IR8 had a short growth period and greater yield potential because of more efficient biomass partitioning, were short-statured and lodging-resistant, and responded well to fertilizer N additions. The use of external inputs such as fertilizers, water, energy, and pesticides increased and the diversity of rice varieties used in irrigated systems decreased. The higher yield potential of modern varieties promoted private and public investments in irrigation infrastructure. Tillage and management intensity improved through extension programs and soils remained submerged for longer periods. Two to three rice crops per year became a reality. Average grain yield reached 4.9 t $ha^{-1}$ in 1991 (Cassman and Pingali 1995b) and harvesting techniques changed. To facilitate land preparation for the next crop, farmers started to cut the entire crop and remove or burn the straw (Uexkuell and Beaton 1992). Since the mid-1980s, trends of declining factor productivity have been noted in long-term rice monoculture and, later, rice-wheat experiments (Flinn and De Datta 1984, Cassman et al 1995, Nambiar 1995). There is evidence that the declining productivity trends come from a gradual degradation of soil quality caused by intensive cropping. Reduced soil N-supplying capacity was identified as a driving force, despite conservation or even an increase in total soil organic matter content (Cassman et al 1995, Cassman and Pingali 1995a). Depletion of soil nutrient reserves, buildup of soil pests, physicochemical changes in the soil caused by increased submergence, and changes in soil microflora were also listed as possible causes of the productivity decline, but universal mechanisms have not yet been identified.

There are numerous examples of soil nutrient depletion other than soil N in intensive rice systems. In productive soils of the alluvial floodplains of South and Southeast Asia, P and K rarely limited rice productivity before these systems were intensified (Kawaguchi and Kyuma 1977, De Datta and Mikkelsen 1985, Bajwa 1994). In most early fertilizer trials with modern varieties, no significant responses to P or K additions were observed, whereas tremendous yield gains could be achieved by applying N fertilizer.

Depletion of extractable soil P to a level that significantly reduced N use efficiency and grain yield was first shown in long-term experiments in the Philippines (De Datta et al 1988). Similar effects were noted in long-term experiments in China. Across 11 sites in five countries, the negative P balance averaged -7 to -8 kg $ha^{-1}$ per crop in zero-P treatments, whereas fertilizer P rates of 17–25kg $ha^{-1}$ were required to maintain the P balance or to increase total soil P (Fig. 1; Dobermann et al 1996b).

Potassium deficiency has become a constraint in soils that were previously not considered as K-limited (Chen et al 1992, Mohanty and Mandal 1989, De Datta and Mikkelsen 1985, Uexkuell 1985, Dobermann et al 1996c, Oberthuer et al 1996). Modern rice varieties require similar amounts of K and N (20 kg of each per ton of grain yield). Most rice farmers in Asia do not apply much fertilizer K, and, as a result of intensification, straw was increasingly removed from the field. In long-term experiments at 11 sites, the K balance was highly negative in all NPK combinations tested (-34 to -63 kg $ha^{-1}$ per crop cycle, Fig. 1) and even fertilizer K application at an average rate of 40 kg $ha^{-1}$ in the +NK and +NPK treatments was not enough to match the K removal at most sites (Dobermann et al 1996c). Examples of K depletion observed in farmers' fields include alluvial, illitic soils in India (Tiwari 1985), lowland rice soils of Java, Indonesia (Sri Adiningsih et al 1991), and vermiculitic clay soils of Central Luzon, Philippines (Oberthuer et al 1996). Although researchers started to raise concern about the danger of negative K balances and soil K depletion many

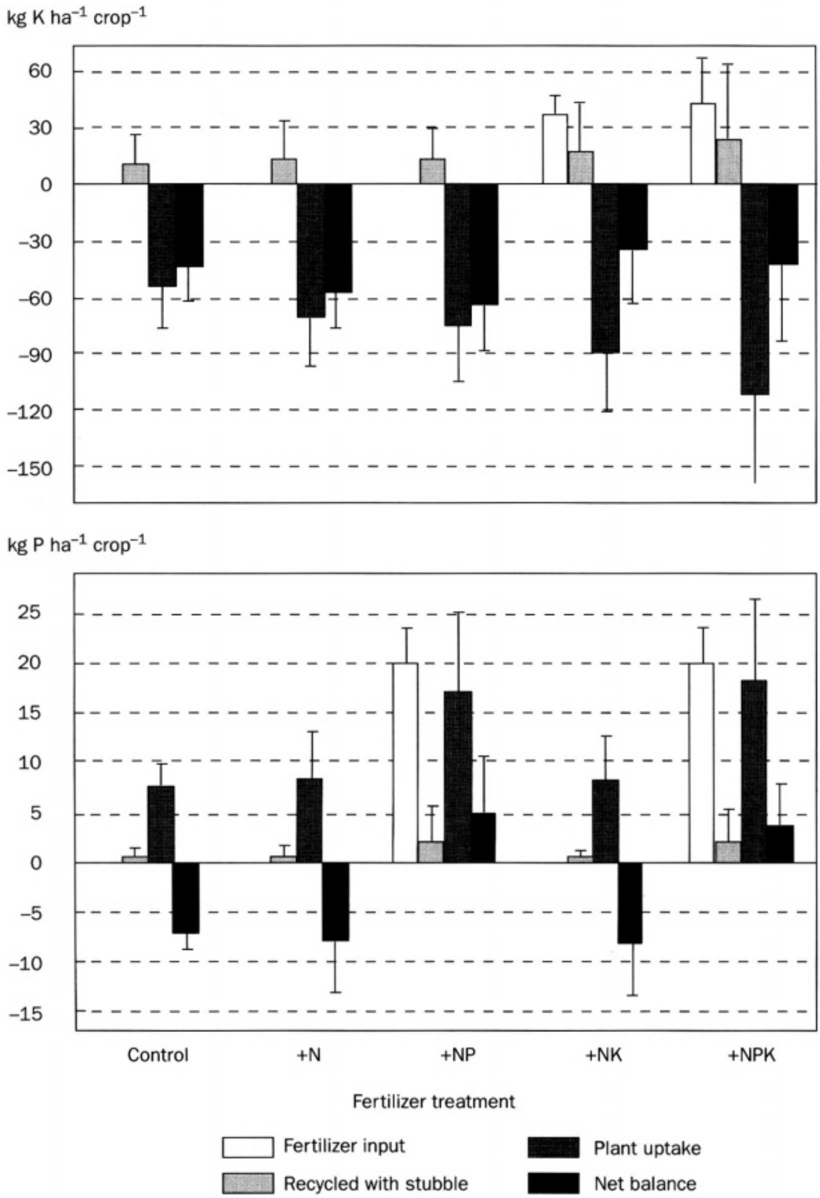



**Fig. 1.** Partial net K and P balance for one rice crop in five different fertilizer treatments. Values shown are averages and standard deviations (error bars) of long-term experiments at 11 sites in five countries sampled in 1993. Stubble was recycled at five sites and all straw was removed at six sites, reflecting standard farmer practices for each location.

years ago (Uexkuell 1985, De Datta and Mikkelsen 1985, Kemmler 1980), this has not yet led to a significant improvement of K management.

Intensification also contributed to more widespread occurrence of S and Zn deficiencies in marginally productive lowland rice soils (Uexkuell and Beaton 1992, Blair et al 1978). The removal or burning of straw or the replacement of sulfur-containing fertilizers with non-S fertilizer (Yoshida 1981) contributed to S depletion in several rice areas. More recently, however, increased air pollution and S deposition associated with rapid industrial development seem to counteract this trend in some parts of South and Southeast Asia. Little is known about Zn balances in traditional and intensive irrigated rice culture. Zinc deficiency is usually associated with leached ultisols and oxisols with high pH or high amounts of organic matter, but Zn depletion may also occur in nonalkaline soils with ZnS formation (Oberthuer et al 1996).

On marginally productive and highly weathered soils, the increased supply of N intensified deficiencies in K, P, and Zn, resulting in the spread of a nutritional disorder known as iron toxicity (Ottow et al 1981).

There is limited quantitative information on the effect of prolonged submergence on the soil's physicochemical properties and its effects on nutrient supply. Though most irrigated rice lands are probably not prone to salinization, the long-term use of poor-quality irrigation water may cause undesirable changes in soil chemistry. Because of the precipitation of carbonates, soil pH may increase (Marx et al 1988). In some areas where groundwater is the irrigation source, high net additions of Ca and Mg may result in reduced K availability because of a wide (Ca + Mg)/K ratio (Dobermann et al 1995). We do not have enough quantitative information about the importance of such processes for sustaining soil quality.

## Effect of intensification on the organic phase

Crop intensification increases the total pool of organic matter in the soil because of intensified root formation and root exudation, and decreased mineralization processes under anoxic conditions (Olk and Cassmann 1995). Photosynthetic primary production in the floodwater provides another soil organic matter source. An average fraction of 1–5% of soil organic matter accounts for living biomass (Anderson and Domsch 1980, Inubushi and Watanabe 1986). This consists mainly of heterotrophic microorganisms and represents an easily available pool of nutrients with a rapid turnover rate (Lee 1994).

Traditional rice cultivation owed most of its sustainability to the continuous replenishment of the organic matter pool (Bray 1986). As a result of the faster turnaround time between intensified crops, farmers eliminate the entire crop from the field and often burn the straw (Uexkuell and Beaton 1992). The intensified cultivation of higher yielding, less photoperiod-sensitive varieties with shorter growth periods required roughly a doubling of the soil nutrient supply. Mineral fertilizers can rapidly and efficiently satisfy this growing demand when bypassing removal in nutrient cycling or the retarding sequences of sequestration and remobilization (Broadbent 1984).

Tropical wetland soils are known for their rapid decomposition of organic debris (Kimura et al 1990). Nevertheless, total soil organic carbon content seems to be conserved or even enhanced in long-term trials under intensive double or triple cropping for decades, though it is partially attenuated by decreasing bulk density (Cassman and Pingali 1995a,b). This may be an indirect evidence of fertilizer-induced, largely microbial, soil organic matter production (Broadbent 1984). Although biomass pools in the photosynthesis-dominated floodwater subsystem are small, its autotrophic productivity can reach 600 kg $ha^{-1}$ over a cropping period (Saito and Watanabe 1978).

Intensification of lowland rice crops implies extended periods of submergence. Thus, anoxic conditions prevailing in the bulk soil can both slow down the primary attack of extracellular enzymes on particulate organic matter (Reichardt 1986) and modify the metabolic pathways of microbial mineralization (Schink 1988). Finally, humification processes involving the buildup of phenolic compounds depend strongly on the chemical composition of the organic input in the submerged system. In contrast to green manure, rice straw may release high amounts of phenolic compounds (Tsutsuki and Ponnamperuma 1987). Polymerization and mineralization of phenols are delayed under anaerobic conditions, which favor the accumulation of young, low-humified soil organic matter that is rich in phenols (Ye and Wen 1991, Palm and Sanchez 1991, Becker et al 1994a, Olk and Cassmann 1995). N-containing aromatic compounds could give a mechanistic explanation for the declining endogenous N supply in continuously flooded anaerobic fields (Cassmann et al 1995).

## Have rice cropping systems become less sustainable since the advent of the Green Revolution?

Irrigated rice systems in tropical Asia will remain the major source of food production in the region, but their sustainable management represents an enormous challenge. Because of increased cropping intensity and yields, the pressure on the soil resource base has increased tremendously. Yield decline, changes in organic matter quality, and nutrient depletion seem to indicate that modern intensive rice systems are less sustainable than the traditional rice culture practiced for thousands of years. Both increased nutrient demand and prolonged submergence seem to cause gradual changes in soil quality that need to be managed.

Some sustainability issues in irrigated rice, such as negative nutrient balances, clearly result from inadequate soil and crop management. Loss of indigenous nutrient supply and negative nutrient balances are the key factors that may reduce the ability of the soil resource base to sustain high rice yields. The seed and fertilizer package approach used during the Green Revolution in Asia did not address such problems adequately. Nutrient management practices of most rice farmers in Asia focus on optimizing short-term gains rather than sustaining soil quality over the long run (Uexkuell and Beaton 1992). Exploiting native soil fertility prevails over maintaining or enhancing soil fertility. The diverse nature of the soil resource base, particularly the large variation in indigenous nutrient supply, has not been taken into account adequately. The importance of returning at least part of the rice straw for soil organic matter conservation and the nutrient balance is well known, but, for various reasons, is widely neglected in current field management. Therefore, some negative trends in productivity are probably reversable through site-specific nutrient management approaches that focus on optimizing nutrient use efficiency in combination with long-term soil fertility management (Dobermann et al 1996a). Such a fine-tuning of system performance will probably significantly improve the productivity and sustainability of intensive rice systems.

The preservation of natural resources depends on a system's environmental sustainability. The latter is often viewed in terms of biodiversity (Schoenly et al, this volume, Chapter 17). There are numerous examples of a reduction in genetic richness and organismic diversity caused by agronomic land use, both among flora and fauna (Schoenly et al 1996a,b, this volume, Chapter 17) and among microorganisms (Torsvik et al 1990).

Microorganisms serve key functions that are also crucial for agronomic sustainability (Chapin et al 1997). This refers to nutrient cycling as well as to the incidence of pathogens and their antagonists. A preliminary comparison of a wetland soil left fallow with a continuously cropped soil of the same texture indicates that intensive irrigated rice cropping can substantially reduce microbial functional diversity (Fig. 2; Reichardt et al 1996).

Problems with agronomic sustainability such as declining yields have been observed in a few long-term experiments with good nutrient management in both predominantly anaerobic (rice-rice) and anaerobic-aerobic (rice-wheat) cropping systems. Identifying the causes for this remains a challenge. At this stage, at what productivity level intensive rice systems can become environmentally and economically sustainable is an open question.

## Options for sustaining the soil resource and functions

### Monocropping versus diversification

Cassman and Pingali (1995b) discussed a reduction in the intensity of flooded rice monocropping by diversifying into higher-value nonrice crops in rotation with rice. In flooded rice systems with two to three crops per year, diversification means providing an aerated upland crop phase. Provision of an aerated phase between two flooded rice crops would reverse the buildup of phenol-rich humic compounds (Olk et al 1996) that may cause a reduction in N availability (Cassman et al 1995). An aerated phase long enough to grow an upland crop is justified, if the total productivity is maintained or even enhanced, provided the quality of the resource base is not adversely affected.

Recent research in favorable rainfed lowland rice systems (George et al 1992, 1993, 1994, 1995) indicates that total productivity can indeed be increased by proper management of dry-season and dry-to-wet-season transition vegetation including grain and green manure legume crops. Without an enhancement in total productivity, short periods of aerated phase between flooded rice could likely provide the same benefits as a whole aerated crop in terms of soil aeration, organic matter decomposition and

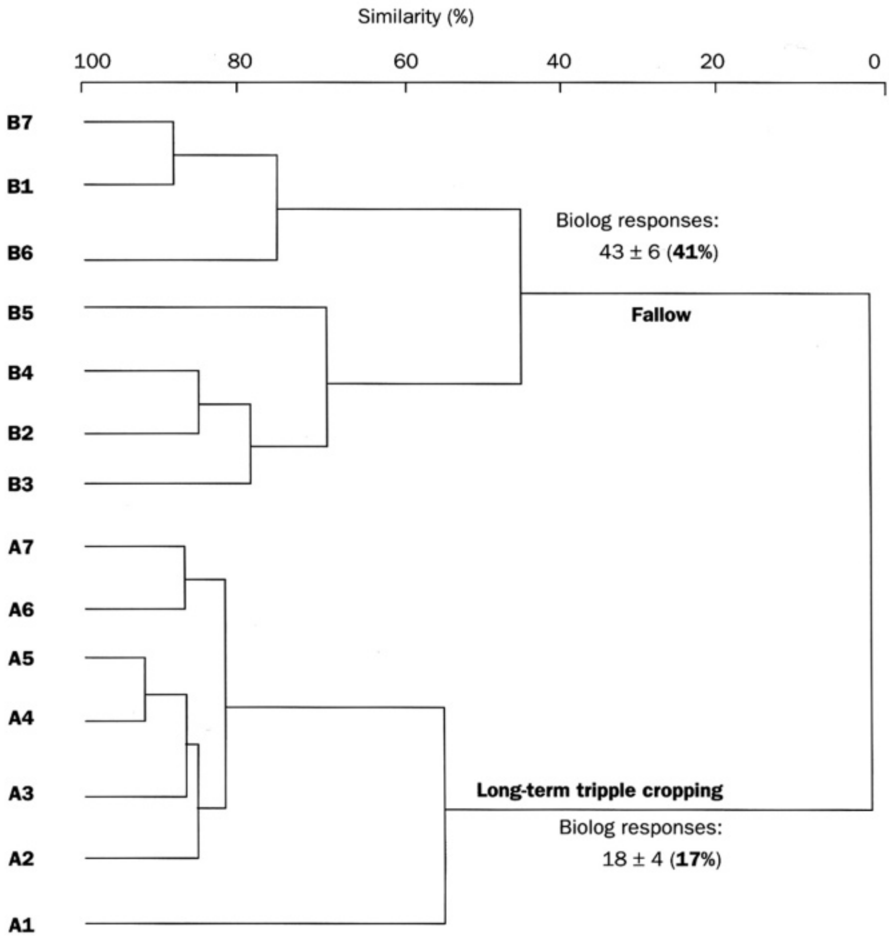



**Fig. 2.** Distinct similarity profiles based on 58 phospholipid fatty acid biomarkers, with positive Biolog® test scores of microbial functions in submerged fallow and triple-cropped rice soils at the IRRI farm, Laguna, Philippines.

formation, and microbial activity. On the other hand, an aerated soil phase may not always be possible because of the heavy clay texture of rice lowlands in the humid tropics. In regions with coarse-textured soils where rice-vegetable rotation cropping is practiced, the excessive use of agrochemicals for the dry-season crops already threatens to lower the quality of the entire resource base. Rice-wheat systems are facing soil quality problems, too (Hobbs et al 1996, Nambiar and Abrol 1989). Thus, diversification alone does not necessarily solve the problems associated with intensification in the irrigated rice lowlands, although it can be part of an overall solution.

It may be that crop diversification would become mandatory in the current intensively cultivated irrigated rice systems with the prospect of water becoming a premium commodity. Developing high-value rice-nonrice crop systems such as rice-soybean or rice-vegetables is a real possibility with the ever-increasing urban demand for water.

### Balancing nutrient inputs and outputs

Substantial quantities of N, P, K, and S are removed from the soil with each crop. Maintaining nutrient balances is therefore a prerequisite for sustaining the resource base. Although our understanding of nutrient cycling in the intensive irrigated rice system has improved, this has not led to measurable improvements in nutrient management practices in farmers' fields. Farmers' decisions about fertilizer application are often more affected by socioeconomic factors (market availability, prices, availability of money) than by biophysical needs. Farmer adoption of existing technology and recommended practices is confounded by considerable field-to-field variability in the indigenous soil nutrient supply.

To achieve and sustain average yields greater than 7–8 t $ha^{-1}$, the nutrient use efficiency from both indigenous and external sources will have to be increased. This implies that nutrient management recommendation domains would have to shift from large regions to farms, single fields, or even single parcels within a larger field.

Knowledge-based objectives and tactics for management differ for each essential nutrient (Dobermann et al 1996a). Adjusting the quantity of applied N to variations in the indigenous N supply is as important as timing, placement, and source of applied N (Peng et al 1996, Cassman et al 1996). Because nutrients such as P and K are not easily lost or added to the root zone by the biological and chemical processes affecting N, their management requires a long-term strategy that emphasizes maintenance of soil nutrient supply to ensure that crop growth and N use efficiency are not limited. Diagnosis of potential deficiencies is the key management tool for nutrients such as Mg, Zn, and S. Once identified as a problem, deficiencies can be alleviated by regular or irregular (single) measures as part of a general fertilizer/soil use recommendation (Dobermann et al 1996a). Straw management is a key leverage point for maintaining a positive balance of most nutrients, particularly for N and K (Becker et al 1994b, Dobermann et al 1996c, 1998). Increasing combine or stripper harvesting may provide new opportunities for better crop residue recycling.

Implementing site-specific management will only be successful if the additional labor required is restricted to a minimum, if the economic gain is sufficient, and if suitable easy-to-use decision aid tools become available. In many Asian countries, facilities for more sophisticated farmer support need to be built up. Included among these are soil-testing laboratories and a soil-testing program (perhaps with the involvement of the private sector), fertilizer recommendation services, objective information about new fertilizer products, and the use of mass media (radio, TV, newspapers) for extension of new technologies. Because the transition to farm- or field-specific management will take time, other cost-effective ways to increase nutrient use efficiencies must be further explored over the shorter term (Pingali et al 1998).

### Managing the organic phase in rice soil/floodwater systems

More than 100 million tons of rice straw are estimated to be produced annually in Southeast Asia, but only a small fraction is presently reincorporated into the soil (Blair et al 1995). Also, enrichment of the organic phase with $N_2$-fixing green manure has ceased in many areas with progressing intensification, as its main purpose of providing sufficient N was no longer served (Becker et al 1994a,b, George et al 1998). With a change in economic conditions, however, the use of green manure could resume, possibly supplementing the use of inorganic N fertilizer as part of integrated nutrient management strategies. Fallow periods of only 40–60 d in intensive systems would limit the use of leguminous green manure to the fastest growing short-duration legumes such as the stem-nodulating *Sesbania rostrata* (Singh et al 1991, Ventura and Watanabe 1993, George et al 1993, 1998).

Because green manure is chosen for its capacity to accumulate N from $N_2$ fixation, its performance is judged in terms of the agronomic efficiency of its N component (Morris et al 1986, Becker et al 1994b). This efficiency is comparable to that of inorganic fertilizer only at N levels below 100 kg $ha^{-1}$ (Singh et al 1991). Nitrogen input, however, would not be the only criterion to justify the use of green manure. In China, a number of K-rich green manure plants have proved successful as potash fertilizers with the beneficial side effect of enhanced protein content in the grain (Peng and Yi 1992). Grown *in situ,* however, such green manure plants do not contribute to a net addition of K to the soil. The complex effects of organic matter inputs on soil quality improvement are also reflected in soil reclamation practices. Green manuring has been shown to be effective in accelerating the reclamation of saline and sodic soils (Singh et al 1991).

Management of organic matter has not kept pace with the recent intensification of rice systems. Success hinges on a clearer understanding of how the network of biogeochemical pathways is regulated. Part of the mineral fertilizers is also assimilated by a dynamic, metabolizing matrix of active biomass and organic matter that forms the system's food web (see Nannipieri et al 1994, Clarholm 1994; Fig. 3). Improved management of the organic matter in the soil means that nutrient release is keeping pace with crop demand. This is achieved by making use of the dynamics of the biota in the rice soil/floodwater systems as the most labile fraction of organic matter (Nannipieri et al 1994).

Current knowledge gaps concerning nutrient supply to lowland rice are further illustrated by the fact that soil nutrient analyses refer to the submerged, anoxic bulk soil, whereas an envelope of oxygen surrounding the roots creates a completely different microenvironment for nutrient uptake (Armstrong 1967, Kirk et al 1993, Revsbech and Reichardt, unpublished).

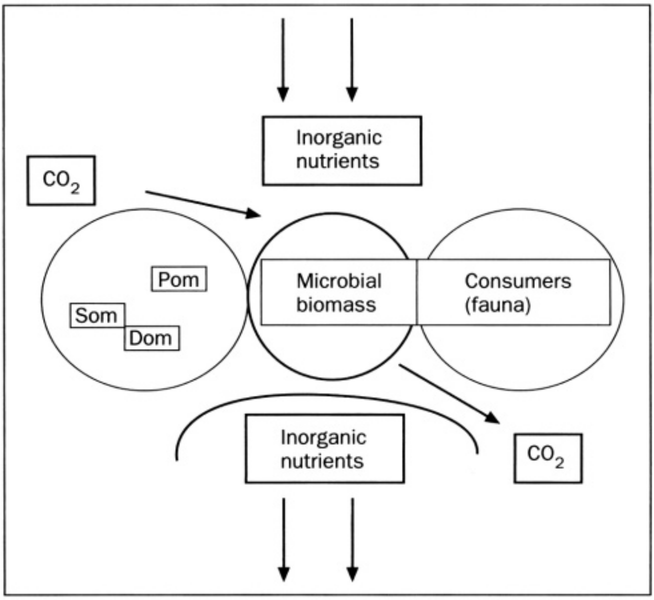



**Fig. 3.** Central role of microbial biomass in nutrient immobilization and release. Pom = particulate organic matter, Dom = dissolved organic matter, Som = soil organic matter.

## Is organic farming a viable option in highly intensified systems?

Organic farming, a practice that uses only organic inputs for production, is sometimes claimed to be the way to attain sustainable crops. Yet there are considerable doubts whether organic inputs alone can sustain high levels of production in intensified systems without polluting the resource base, including its drainage area. For example, the excessive use of green manure will cause the release of nitrate and ammonium from the unused fraction of the organic input. There is growing evidence that this can lower the quality of the resource base, the same as the excessive use of inorganic N fertilizers (George et al 1993, 1994, 1998).

A serious practical problem for intensive organic rice farming on a large scale would be generating the quantities of organic nutrients (not to mention their transportation costs) that are required to compensate for nutrient depletion after each harvest. So far, we have not seen convincing evidence that the supply of nutrients from organic sources to highly intensive cropping systems can be managed on a large scale. There seems to be much more potential for improving the integrated use of nutrients from inorganic and organic sources as appropriate to sustain productivity at high yield levels. The bottom line is that rice production must keep pace with the demand for rice by the ever-increasing rice-eating population.

## Caveat: moving intensified rice cultivation to the uplands?

Wetland rice production systems apparently owe much of their sustainability to flooding. Processes in the floodwater component and submergence of the soil create the chemical and biological basis for a continuous renewal of the system's soil fertility (Ponnamperuma 1984, Roger 1996). Hence, it seems inevitable that most rice is produced in irrigated systems. Yet the majority of the world's rice area is rainfed. Further, these less productive rice areas, in particular the uplands, are inhabited by the poorest farmers. Productivity gains should obviously be achieved in these presently less productive areas. But how sustainable will these rainfed systems be if we intensify rice production? Indications are that intensification is possible, but only in the limited, more favorable rainfed areas, including the uplands. If total rice production on all rice land were maintained at the same level as in irrigated systems (4.9 t $ha^{-1}$), global production would reach 727 million t. But because of the marked differences in production systems, real production falls 207 million t short of that figure (Prasad et al 1995).

Because of the increasing water shortage, the potential and sustainability of less water-intensive alternatives to the present irrigated rice systems will have to be explored. Limited areas in the uplands, where the rainy season is relatively free of drought spells and the land is flat to moderately sloping, have the potential for intensified crop production that includes rice. Though severely deficient in nutrients and usually highly acidic (Sanchez 1976), the highly weathered tropical upland soils possess the best physical properties for supporting crop production (Sanchez and Logan 1992). Phosphorus limitation is an example of a serious constraint even in traditional upland rice production (Fig. 4). Yet substantial productivity gains are possible once nutrient deficiencies and problems associated with soil acidity have been overcome (Sanchez and Logan 1992, Cassman et al 1993, Uexkuell and Mutert 1995). An example of a favorable rainfed upland is the *cerrado* ecosystem in Brazil. Its approximately 100 million ha of highly acidic upland soil could be reclaimed. In addition, large-scale mechanization in rice production is possible, as the first attempts in a few areas have shown. For the less favorable, fragile agroecosystems, the obstacles to sustaining the resource base outweigh the gains in most instances and regions.

## Opportunities for short-term measures of environmental sustainability

Agronomic sustainability, which implies stable productivity, is reflected in measures such as annual yield records, partial factor productivity, or nutrient balances that can be monitored with each crop. Useful as they are, such tong-term records can only give an incomplete account of the total factor capacity of the resource base to sustain high yields. Being production-targeted, they do not include aspects of the environmental quality of the flooded resource base.

Ultimately, productivity and environmental quality of a rice field are both linked to processes in the organic phase. Here, microorganisms are the main carriers of biocatalytic functions (Chapin et al 1997). They affect nutrient supply to the crop as well as the cycling of bioelements, which is a crucial function in any ecosystem. This

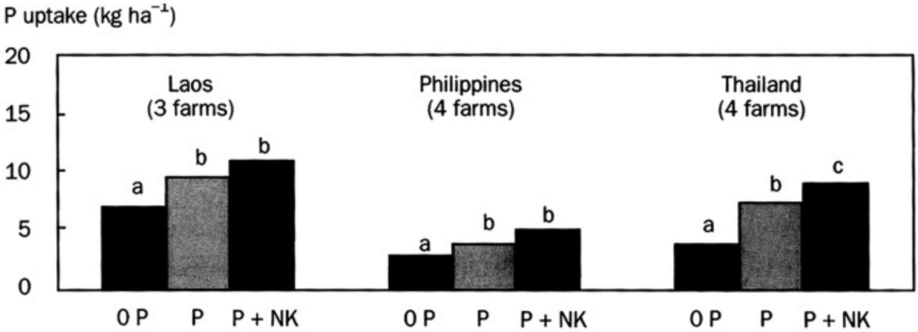



**Figure 4.** Phosphorus uptake by traditional upland rice in response to near-non-limiting applications of P with and without nitrogen and potassium in Southeast Asian uplands, 0 P = no P, P = 50 kg P $ha^{-1}$, and P + NK = 50 kg P $ha^{-1}$ plus 100 kg N $ha^{-1}$ and 50 kg K $ha^{-1}$. Columns under each country are not significantly different by LSD (0.05) if indicated by the same lowercase letter. (George, unpublished.)

linkage allows us to look for promising combined measures of yield- and ecosystem-related sustainability (Matson et al 1997).

Rapid progress in microbial ecology provides a number of options for short-term assays to quantify the sustainability of biocatalytic functions in the soil environment. One such category of assays targets certain enzymatic processes as potential indicators of functional imbalances in an ecosystem (Reichardt et al 1993, Reichardt 1996). The relatively new discipline of ecotoxicology, which focuses on man-made damage to ecosystem functions and environmental health, has adopted biochemical techniques that were designed for holistic analyses of ecosystem functions.

Another category on which potential measures of environmental sustainability are based involves the concept of functional microbial diversity and richness (Atlas 1984, Coleman et al 1994). It partly requires advanced techniques such as biomarker analysis (Tunlid and White 1992, Reichardt et al 1997). An alternative methodology is based on substrate mineralization patterns (Zak et al 1994, Reichardt et al 1996, 1997). The principle on which commercially available test kits such as Biolog (Zak et al 1994, Schoenly et al, this volume, Chapter 17) are already based might eventually allow rapid tests of functional sustainability to be carried out in farmers' fields.

Notwithstanding the potential role of biodiversity as an indicator of an agroecosystem's sustainability (Chapin et al 1997, Matson et al 1997), intensified lowland rice production systems are composed of an extremely large number of very diverse microbial subhabitats in space and time (Schoenly et al, this volume, Chapter 17). The floodwater compartment with its primary production in particular is viewed as a major supporter of the system's sustainability (Roger 1996). Moreover, under conditions that are conducive to aquaculture at the same time, a potent "natural" toxicity testing system could become available to farmers (Dela Cruz et al 1992).

## References


Anderson JPE, Domsch KH. 1980. Quantities of plant nutrients in the microbial biomass of selected soils. Soil Sci. 130:211-216.

Atlas RM. 1984. Use of microbial diversity measurements to assess environmental stress. In: Klug JM, Reddy CA, editors. Perspectives in microbial ecology. Proceedings of an International Symposium on Microbial Ecology, East Lansing, Mich. p 540-545.

Armstrong W. 1967. The oxidizing activity of roots in waterlogged soils. Physiol. Plant. 20:920-926.

Bajwa MI. 1994. Soil potassium status, potash fertilizer usage and recommendations in Pakistan. Potash Review No. 3/1994. Subject 1, 20th suite. Base1 (Switzerland): International Potash Institute.

Becker M, Ladha JK, Simpson IC, Ottow JCG. 1994a. Parameters affecting residue nitrogen mineralization in flooded soils. Soil Sci. Soc. Am. J. 58:1666-1671.

Becker M, Ladha JK, Ottow JCG. 1994b. Nitrogen losses and lowland rice yield as affected by residue nitrogen release. Soil Sci. Soc. Am. J. 58: 1660-1665.

Blair GJ, Mamaril CP, Momuat E. 1978. Sulfur nutrition of wetland rice. IRRI Research Paper Series 21. Manila (Philippines): International Rice Research Institute.

Blair G, Lefroy R, Konboon Y, Wonprasaid S, Naklang K. 1995. Carbon and nutrient pools in rice cropping systems. In: Fragile lives in fragile ecosystems. Manila (Philippines): International Rice Research Institute. p 161-172.

Bray F. 1986. The rice economies: technology and development in Asian societies. London (UK): B. Blackwell.

Broadbent FE. 1984. Plant use of soil nitrogen. In: Nitrogen in crop production. Madison, Wis. (USA): ASA-SSSA. p 171-182.

Cassman KG, Singleton PW, Linquist BA. 1993. Input/output analysis of the cumulative soybean response to phosphorus on an Ultisol. Field Crops Res. 34:23-36.

Cassman KG, De Datta SK, Olk DC, Alcantara J, Samson M, Descalsota JP, Dizon M. 1995. Yield decline and the nitrogen economy of long-term experiments on continuous, irrigated rice systems in the tropics. In: Lal R, Stewart BA, editors. Sustainable management of soils. Michigan (USA): Lewiston Publishers, CRC Press Inc. p 181-222.

Cassman KG, Gines GC, Dizon M, Samson MI, Alcantara JM. 1996. Nitrogen-use efficiency in tropical lowland rice systems: contributions from indigenous and applied nitrogen. Field Crops Res. 47:l-12.

Cassman KG, Pingali PL. 1995a. Extrapolating trends from long-term experiments to farmers' fields: the case of irrigated rice systems in Asia. In: Barnett V, Payne R, Steiner R, editors. Agricultural sustainability in economic, environmental, and statistical terms. London: J. Wiley & Sons. p 64-84.

Cassman KG, Pingali PL. 1995b. Intensification of irrigated rice systems: learning from the past to meet future challenges. GeoJournal 35:299-305.

Chapin FS, Walker, BH, Hobbs RJ, Hooper DU, Lawton JH, Sala OE, Tilman D. 1997. Biotic control over the functioning of ecosystems. Science 277:500-504.

Chen FX, Chen YA, Zou CM. 1992. Potassium balance in red earth paddy soil of Southern Hunan and its application. Proceedings of the International Symposium on Paddy Soils. Nanjing (China): Chinese Academy of Sciences. p 193-194.

Clarholm M. 1994. The microbial loop in soil. In: Ritz K, Dighton J, Giller KE, editors. Beyond the biomass. Chichester: J. Wiley. p 221-230.

Coleman DC, Dighton J, Ritz K, Giller KE. 1994. Perspectives on the compositional and functional analysis of soil communities. In: Ritz K, Dighton J, Giller KE, editors. Beyond the biomass. Chichester: J. Wiley. p 261-270.

De Datta SK, Gomez KA, Descalsota JP. 1988. Changes in yield response to major nutrients and in soil fertility under intensive rice cropping. Soil Sci. 146:350-358.

De Datta SK, Mikkelsen DS. 1985. Potassium nutrition of rice. In: Munson RD, Sumner ME, Bishop WD, editors. Potassium in agriculture. Madison, Wis. (USA): ASA, CSSA, SSSA. p 665-699.

Dela Cruz CR, Lightfoot C, Costa-Pierce BA, Carangal VC, Bimbao MP. 1992. Rice-fish research and development in Asia. ICLARM Conf. Proc. No. 24. Manila (Philippines): International Center for Living Aquatic Resources Management.

Dobermann A, Cassman KG, Peng S, Pham Sy Tan, Cao Van Phung, Sta. Cruz PC, Bajita JB, Adviento MAA, Olk DC. 1996a. Precision nutrient management in intensive irrigated rice systems. In: Attanandana T, Kheoruenromne I, Pongsakul P, Vearasilp T, editors. Proceedings of the International Symposium on Maximizing Sustainable Rice Yields Through Improved Soil and Environmental Management. Khon Kaen, Thailand. p 133-154.

Dobermann A, Cassman KG, Mamaril CP, Sheehy JE. 1998. Management of phosphorus, potassium, and sulfur in intensive, irrigated lowland rice. Field Crops Res. 56:113-138.

Dobermann A, Cassman KG, Sta. Cruz PC, Adviento MAA, Pampolino ME 1996b. Fertilizer inputs, nutrient balance, and soil nutrient-supplying power in intensive, irrigated rice systems. III. Phosphorus. Nutr. Cycl. Agroecosys. 46:111-125.

Dobermann A, Sta. Cruz PC, Cassman KG. 1995. Potassium balance and soil potassium supplying power in intensive, irrigated rice ecosystems. In: Potassium in Asia. Proc. of the 24th International Colloquium of the International Potash Institute, 21-24 Feb. 1995, Chiang Mai, Thailand. Basel (Switzerland): IPI. p 199-234.

Dobermann A, Sta. Cruz PC, Cassman KG. 1996c. Fertilizer inputs, nutrient balance, and soil nutrient-supplying power in intensive, irrigated rice systems. I. Potassium uptake and K balance. Nutr. Cycl. Agroecosys. 46:l-10.

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

George T, Ladha JK, Buresh RJ, Garrity DP. 1992. Managing native and legume-fixed nitrogen in lowland rice-based cropping systems. Plant Soil 141:69-91.

George T, Ladha JK, Buresh RJ, Garrity DP. 1993. Nitrate dynamics during the aerobic soil phase in lowland rice-based cropping systems. Soil Sci. Soc. Am. J. 57:1526-1532.

George T, Ladha JK, Garrity DP, Buresh RJ. 1994. Legumes as “nitrate catch” crops during the dry-to-wet transition in lowland rice cropping systems. Agron. J. 86:267-273.

George T, Ladha JK, Ganity DP, Torres RO. 1995. Nitrogen dynamics of grain legume-weedy fallow-flooded rice sequences in the tropics. Agron. J. 87:l-6.

George T, Buresh RJ, Ladha JK, Punzalan G. 1998. Recycling *in situ* of legume-fixed and soil nitrogen in tropical lowland rice. Agron. J. (In press.)

Hobbs PR, Harrington LW, Adhikary C, Gin GS, Upadhyay SR, Adhikary B. 1996. Wheat and rice in the Nepal Tarai: farm resources and production practices in Rupandehi district. NARC, International Maize and Wheat Improvement Center (CIMMYT), Mexico, D.F.

Inubushi K, Watanabe I. 1986. Dynamics of available nitrogen in paddy soils. II. Mineralized N of chloroform-fumigated soil as a nutrient source for rice. Soil Sci. Plant Nutr. 32:561-577.

Kawaguchi K, Kyuma K. 1977. Paddy soils in tropical Asia: their material nature and fertility. Honolulu, Hawaii (USA): The University Press of Hawaii.

Kemmler G. 1980. Potassium deficiency in soils of the tropics as a constraint to food production. In: Priorities for alleviating soil-related constraints to food production in the tropics. Manila (Philippines): International Rice Research Institute. p 253-275.

Kimura M, Watanabe I, Patcharapreetcha P, Panichsapatana S, Wada H, Takai Y. 1990. Quantitative estimation of decomposition process of plant debris in paddy field. Soil Sci. Plant Nutr. 36:33-42.

Kirk GJD, Begg CBM, Solivas JL. 1993. The chemistry of the lowland rice rhizosphere. Plant Soil. 155/156:83-86.

Lee KE. 1994. The diversity of soil organisms. In: Hawksworth DL, editor. The biodiversity of microorganisms and invertebrates: its role in sustainable agriculture. Wallingford (UK): CAB International. p 73-87.

Mam DB, Gilmour JT, Scott HD, Ferguson JA. 1988. Effects of long-term water management in a humid region on spatial variability of soil chemical status. Soil Sci. 145:188-193.

Matson PA, Parton WJ, Power AG, Swift MJ. 1997. Agricultural intensification and ecosystem properties. Science 277:504-509.

Mohanty SK, Mandal LN. 1989. Transformation and budgeting of N, P and K in soils for rice cultivation. Oryza 26:213-231.

Moms RA, Furoc RE, Dizon MA. 1986. Rice responses to a short-duration green manure. I. Grain yield. Agron. J. 78:409-412.

Nambiar KKM, Abrol IP. 1989. Long-term fertilizer experiments in India: an overview. Fert. News. 34(4):11-20.

Nambiar KKM. 1995. Long-term experiments on major cropping systems in India. In: Barnett V, Payne R, Steiner R, editors. Agricultural sustainability in economics, environmental, and statistical terms. London: John Wiley & Sons.

Nannipieri P, Badalucco L, Landi L. 1994. Holistic approaches to the study of populations, nutrient inputs and fluxes: limitations and future research needs. In: Ritz K, Dighton J, Giller JSE, editors. Beyond the biomass. Chichester: John Wiley. p 231-246.

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

Olk DC, Cassman KG. 1995. Characterisation of two chemically extracted humic acid fractions in relation to nutrient availability. In: Lefroy RDB, Blair GJ, Craswell ET, editors. Soil organic matter management for sustainable agriculture. ACIAR Proceedings No. 56. Ubon, Thailand, 24-26 Aug 1994. ACIAR, Canberra, Australia.

Olk DC, Cassman KG, Randall EW, Kinchesh P, Sangers LJ, Anderson JM. 1996. Changes in chemical properties of organic matter with intensified rice cropping in tropical lowland soil. Eur. J. Soil Sci. 47:293-303.

Ottow JCG, Benckiser G, Watanabe I. 1981. Iron toxicity as a multiple nutritional stress of rice. Giessener Beitrage zur Entwicklungsforschung, I. 7:203-215.

Palm CA, Sanchez PA. 1991. Nitrogen release from the leaves of some tropical legumes as affected by their lignin and polyphenolic contents. Soil Biol. Biochem. 23:83-88.

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.

Peng KL, Yi FX. 1992. The selection and application of potassium-rich green manure. In: Chen L, editor. Proceedings of studies on green manure in China. Shenyang (China): Liaoning University Press. p 66-69.

Pingali PL, Hossain M, Pandey S, Price L. 1998. Economics of nutrient management in Asian rice systems: towards increasing knowledge intensity. Field Crops Res. 56:157-176.

Ponnamperuma FN. 1972. The chemistry of submerged soils. Adv. Agron. 24:29-96.

Ponnamperuma FN. 1984. Effects of flooding on soils. In: Kozlowski TT, editor. Flooding and plant growth. Orlando, Fla. (USA): Academic Press. p 9-45.

Prasad ASR, Prasad GSV, Muralidharan K. 1995. Fragile ecosystems for rice cultivation? In: Fragile lives in fragile ecosystems. Manila (Philippines): International Rice Research Institute. p 369-393.

Reichardt W. 1986. Enzymatic potential for decomposition of detrital biopolymers in sediments from Kiel Bay. Ophelia 28:369-384.

Reichardt W. 1996. Ecotoxicity of certain heavy metals affecting bacteria-mediated biogeochemical pathways in sediments. In: Calmano W, Foerstner U, editors. Sediments and toxic substances: environmental effects and ecotoxicity. Berlin: Springer Verlag. p 159-178.

Reichardt W, Heise S, Piker L. 1993. Ecotoxicity testing of heavy metals using methods of sediment microbiology. Environ. Toxicol. Water Qual. 8:299-311.

Reichardt W, Briones A, Padre B, de Jesus R, Mascariña G. 1996b. Dynamics of soil microbial communities and sustainable nutrient supply in highly intensified rice cultivation. In: Attanandana T, Kheoruenromne I, Pongsakul P, Vearasilp T, editors. Proceedings of the International Symposium on Maximizing Sustainable Rice Yields Through Improved Soil and Environmental Management. Khon Kaen, Thailand. p 887-896.

Reichardt W, Mascariña G, Padre B, Doll J. 1997. Microbial communities of continuously cropped irrigated rice fields. Appl. Environ. Microbiol. 63:233-238.

Roger PA. 1996. Biology and management of the floodwater ecosystem in ricefields. Manila (Philippines): International Rice Research Institute, and France: ORSTOM.

Saito M, Watanabe I. 1978. Organic matter production in rice field floodwater. Soil Sci. Plant Nutr. 28:427-440.

Sanchez PA. 1976. Properties and management of soils in the tropics. New York (USA): John Wiley.

Sanchez PA, Logan TJ. 1992. Myths and science about the chemistry and fertility of soils in the tropics. In: Lal R, Sanchez PA, editors. Myths and science of soils of the tropics. SSSA Spec. Publ. 29. Madison, Wis. (USA): ASA, SSSA. p 35-46.

Schink B. 1988. Principles and limits of anaerobic degradation: environmental and technological aspects. In: Zehnder AJB, editor. Biology of anaerobic microorganisms. New York (USA): John Wiley.

Schoenly KG, Cohen JE, Heong KL, Arida AS, Bamon AT, Litsinger JA. 1996a. Quantifying the impact of insecticides on food web structure of rice-arthropod populations in a Philippine farmer's irrigated field: a case study. In: Polis G, Winemiller K, editors. Food webs: integration of patterns and dynamics. New York (USA): Chapman and Hall. p 343-351.

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

Singh Y, Khind CS, Singh B. 1991. Efficient management of leguminous green manures in wetland rice. Adv. Agron. 45:135-189.

Sri Adiningsih J, Santoso D, Sudjadi M.1991. The status of N, P, K and S of lowland rice soils in Java. In: Blair G, editor. Sulfur fertilizer policy for lowland and upland rice cropping systems in Indonesia. Melbourne (Australia): Australian Centre for International Agricultural Research. p 68-76.

Swaminathan MS. 1991. Sustainable agriculture: need for conceptual clarity. In: Hawksworth DL, editor. The biodiversity of microorganisms and invertebrates: its role in sustainable agriculture. Wallingford (UK): CAB International. p 273-287.

Tiwari KN. 1985. Changes in potassium status of alluvial soils under intensive cropping. Fert. News 30:17-24.

Torsvik V, Sake K, Sorheim R, Goksoyr J. 1990b. Comparison of phenotypic diversity and DNA heterogeneity in a population of soil bacteria. Appl. Environ. Microbiol. 56:776-781.

Tsutsuki K, Ponnamperuma FN. 1987. Behaviour of anaerobic decomposition products in submerged soils. Soil Sci. Plant Nutr. 33:13-33.

Tunlid A, White DC. 1992. Biochemical analysis of biomass, community structure, nutritional status, and metabolic activity of microbial communities in soil. In: Stotzky G, Bollag JM, editors. Soil biochemistry. Vol. 7. New York (USA): Marcel Dekker. p 229-262.

Uexkuell HR von. 1985. Availability and management of potassium in wetland rice soils. In: Wetland soils: characterization, classification and utilization. Manila (Philippines): International Rice Research Institute. p 293-305.

Uexkuell HR von, Beaton JD. 1992. A review of fertility management of rice soils. In: Kimble JM, editor. Characterization, classification, and utilization of wet soils. Proceedings of the 8th International Soil Correlation Meeting (VIII. ISCOM). Soil Conservation Service. Lincoln, Neb. (USA): United States Department of Agriculture. p 288-300.

Uexkuell HR von, Mutert E. 1995. Global extent, development and economic impact of acid soils. Plant Soil 171:l-15.

Ventura W, Watanabe I. 1993. Green manure production of *Azolla microphylla* and *Sesbania rostrata* and their long-term effects on rice yields and soil fertility. Biol. Fert. Soils 15:241-248.

Ye W, Wen QX. 1991. Characteristics of humic substances in paddy fields. Pedosphere 1:229-239.

Yoshida S. 1981. Fundamentals of rice crop science. Manila (Philippines): International Rice Research Institute.

Zak JC, Willig MR, Moorhead DL, Wildman HG. 1994. Functional diversity of microbial communities: a quantitative approach. Soil Biol. Biochem. 26: 1101-1108.

## Notes

*Authors' address:* International Rice Research Institute (IRRI), P.O. Box 933, 1099 Manila, Philippines. w.reichardt@cgnet.com a.dobermann@cgnet.com t.george@cgnet.com

*Acknowledgments:* We would like to thank J.C.G. Ottow, Giessen, Germany, and W.H. Patrick Jr., Baton Rouge, Louisiana, USA, for reviewing an earlier draft.

*Citation:* Dowling NG, Greenfield SM, Fischer KS, editors. 1998. Sustainability of rice in the global food system. Davis, Calif. (USA): Pacific Basin Study Center, and Manila (Philippines): International Rice Research Institute.

CHAPTER 9

# Importance of rice pests and challenges to their management

M.B. Cohen, S. Savary, N. Huang, O. Azzam, and S.K. Datta

New technologies and a greater understanding of the rice ecosystem are contributing to more effective and sustainable pest management in farmers' fields. Prioritizing research on rice pests (insects, plant diseases, and weeds) has been made difficult by a lack of systematic survey data on pest losses in different ecosystems and under different production conditions. To bridge this knowledge gap, work in progress is quantifying risk probability and risk magnitude of pest injuries. Surveys in farmers' fields have been conducted at hundreds of sites in several countries to quantify the risk probability for various pests. Experiments at IRRI have manipulated pest levels under varying production situations to quantify the magnitude of yield loss across these conditions. Researchers are applying biotechnology to produce rice varieties with improved resistance to insects and diseases. Marker-aided selection can improve the efficiency of rice breeding, and be used to "pyramid" multiple genes for resistance to a given pest. Plant transformation enables us to introduce novel resistance genes from any organism into rice. Varietal resistance to pests has many desirable features, such as environmental safety and convenience for farmers, but has suffered from a lack of durability as pest populations adapt to new resistant varieties. Researchers are using DNA fingerprinting to enhance understanding of pest population genetics and behavioral studies of insects to develop resistance management strategies for the sustainable use of resistant cultivars in farmers' fields.

In agriculture, pests (or biotic constraints) can be defined as organisms that cause economic loss. Among the pests that attack rice are insects, microorganisms (viruses, bacteria, and fungi) that cause plant disease, weeds, and even vertebrates such as rats and birds. Pest management has been a dynamic area of research at IRRI since its establishment, driven by the advent of new technologies and improvements in understanding of the rice ecosystem. The roles of two new technologies in pest management, marker-aided selection and genetic engineering, are covered later in this chapter. We also discuss two examples of improved ecosystem understanding: quantification of pest-associated yield losses under different crop production conditions and new approaches to the sustainable use of pest-resistant rice varieties. An ecosystem component now recognized to be of tremendous importance, the beneficial arthropods and microorganisms that feed upon or compete with pest organisms, is reviewed by

Schoenly et al (this volume, Chapter 17) in their paper on arthropod biodiversity and rice landscapes.

The goal of pest research at IRRI is to provide technologies and knowledge that contribute to integrated pest management (IPM) in farmers' fields (IRRI 1994). IPM has become a term with diverse meanings (Waage 1996). As used by IRRI, it refers to achieving low and stable pest populations and reducing chemical pesticide use by improving farmer understanding of the crop ecosystem and combining biological, cultural, and chemical tactics. Pesticides can be major expenses for resource-poor farmers, are often hazardous to the environment and human health (Pingali and Roger 1995), and can exacerbate pest problems by disrupting naturally occurring biological controls (Way and Heong 1994).

## Importance of rice biotic constraints and prioritizing research for their management

This section addresses a number of questions. How important are rice biotic constraints under current agricultural scenarios? How reliable is our assessment of these constraints? What are the implications of foreseeable agricultural changes for the importance of rice biotic constraints? What are the avenues to both predict and manage these constraints in yet-to-come production situations in a sustainable way?

All these questions cannot, of course, be answered in detail here. Rather, this section tries to bring into perspective the close association between changes in production situations and damage caused by rice pests. Such a link implies that the introduction of new agricultural technologies — changes in production situations (De Wit 1982) — will have an effect, positive or negative, on damage from pests. One avenue that we offer for addressing this issue is risk analysis, similar in principle to the approach used in industry (Rowe 1980).

Pest populations building up in crops may have economic, social, and political consequences (Zadoks and Schein 1979). These consequences stem from the diversity of effects or injuries caused by pests (Zadoks 1967): direct losses (in yield, in quality, or costs of replanting) or indirect losses (at the farm, community, or consumer level). Measurement of yield losses therefore only provides a limited view of the impact of pests on crops and societies. Yield loss, however, is associated with a comparatively precise and simple operational definition. Quantitative information on yield losses from pests is necessary to develop policies, to set research priorities, to assess the progress made in protecting crops, and to develop efficient IPM schemes (Zadoks and Schein 1979, Teng 1983). Such information represents level 1 of a process leading to the implementation of a systems approach in pest management (Teng and Savary 1992). Yield loss data attributable to pests are thus all the more necessary when agricultural systems are undergoing rapid and important transformations, such as the rice-based cropping systems of tropical Asia (Hossain, this volume, Chapter 3), so that the risk associated with such changes can be assessed from a plant protection viewpoint (Savary et al 1997).

A review of the literature on rice diseases and insect pests was done over the period 1960-93 using five criteria: (1) reports address rice production in tropical Asia, (2) their main objective is to measure yield loss, (3) they provide descriptions of experimental and sampling designs, (4) they describe the techniques used for both manipulating disease levels (if applicable) and measuring yield variation, and (5) they provide quantitative information on yield losses. Reports were sorted according to the rice ecosystem involved (irrigated, rainfed lowland, flood-prone, and upland; Khush 1984), and ranked by their representativeness with respect to space, time, scale, and injury. Assessments of representativeness of yield loss data (James 1974, Madden 1983) attributable to rice pests over time, space, and scale were based on the proportion of studies conducted over more than 1 year, on the proportion of studies conducted at more than one location, and on the proportion of studies conducted at the plot (>1 $m^2$) or field level, respectively. Representativeness of injury was judged much more difficult to assess. The standard deviation of the proportion of studies using inoculations, spontaneous infection, or chemical control was used as an index. A low standard deviation in one group of studies (e.g., yield losses caused by bacterial diseases) would indicate flexibility in addressing a particular issue and a balance among approaches. The main result of this review is the surprisingly limited number of published reports that we can rely on. Considerable discrepancies have also been found among rice ecosystems in a number of studies, as most of them concentrated on the irrigated ecosystem. Most studies conducted in this ecosystem, however, were conducted at one location and in one season, whereas many studies in the other three ecosystems pertain to several locations in two or more seasons.

We need to better document yield losses in ecosystems other than those in the irrigated one. The potential for extrapolation of results in the irrigated ecosystem deserves consideration, and the representativeness of studies conducted in other ecosystems cannot compensate for their small numbers. Perhaps, more importantly, improving the representativeness of yield loss data in all four ecosystems is necessary to better define the needs of rice production systems.

## A risk-analytical approach for setting priorities

The dynamics of harmful agents may lead to injury—visible signs of their biological activity on the standing crop. Injury may lead to damage and yield loss. Damage may or may not, in turn, lead to yield loss and a reduction of crop value in economic terms (Zadoks 1985). Our focus is on damage, which closely depends on injury via a damage function, which in turn may affect losses via a loss function. Changes in patterns of cropping practices (e.g., inputs) may dramatically alter the physiological reaction of a crop to injury, and therefore the shape of the damage function. Similarly, the occurrence of two different injuries, simultaneously or in sequence, may also modify the damage function. As a result, the damage function, which is the basis of the threshold theory (Zadoks 1985) in plant protection, is very complex, being a product of numerous processes. Changes in patterns of cropping practices are also known to strongly influence population dynamics, and therefore injuries (Teng and Savary 1992, Savary et al 1994). The variation of damage with changing production situations and injury profiles was recently addressed using a risk-analytical approach (Savary et al 1997), which involves two steps: assessing the risk probability P (i.e., the probability of a given injury occurring in a given production situation) and determining the risk magnitude (i.e., the damage associated with that injury). Risk probability can be assessed from surveys in farmers' fields, whereas risk magnitude can be measured in field experiments where both injuries and cropping practices are varied. The risk associated with a particular pest is then determined (Rowe 1980): $R = P \times M$.

## Risk probability: surveys of injuries in farmers' fields

Survey procedures (Elazegui et al 1990, Pinnschmidt et al 1995) have been used in farmers' fields of different countries—the Philippines, India (eastern Uttar Pradesh), Thailand, and Vietnam. The procedures entail quantification of injuries caused by insects, pathogens, and weeds, as well as a description of cropping practices. Figure 1 shows the strong variation in risk probabilities for nine injuries in a few selected rice production situations, especially for two diseases: sheath blight (ShB) or brown spot (BS). Rice tungro disease (RTD) is detected in one production situation at a low risk probability. Insect injuries (deadhearts, DH, and whiteheads, WH, caused by stem-boring caterpillars; and whorl maggot, WM) are omnipresent, often with high risk probabilities. Weed infestation (WA, weed above the rice crop canopy, and WB, weed below the rice crop canopy) appears to be the most common constraint in all production situations, with mostly a high risk probability.

## Risk magnitude: measuring yield losses in controlled experiments

Over the past several years, IRRI has been conducting a series of experiments in which four input factors have been varied (potential yield of the rice cultivar, crop establishment method, water management, and fertilizer supply) and nine injuries have been manipulated (bacterial blight, RTD, BS, ShB, WM, DH, WH, WA, and WB). Each experiment includes noninjured controls for each pattern of cropping practice it addresses, which provide estimates of attainable yields (Ya), and therefore a means to empirically measure yield losses: $YL = Ya - Y$. The resulting experimental yield loss database covers a range of attainable yields from 1 to 11 t $ha^{-1}$, reflecting the variation in production situations.

These data were analyzed with multivariate techniques. One of the resulting empirical models shows significant interactions of Ya and injuries with yield loss variation. In other words, the same injury will have different consequences (Fig. 2), depending on the production situation considered (represented by Ya).

## Risk estimates across production situations

The empirical model was also used to estimate the risk magnitude (% yield loss) in several production situations. Two arbitrary injury levels (high and low) were also considered, based on the range of observed injuries. The resulting estimates for risk

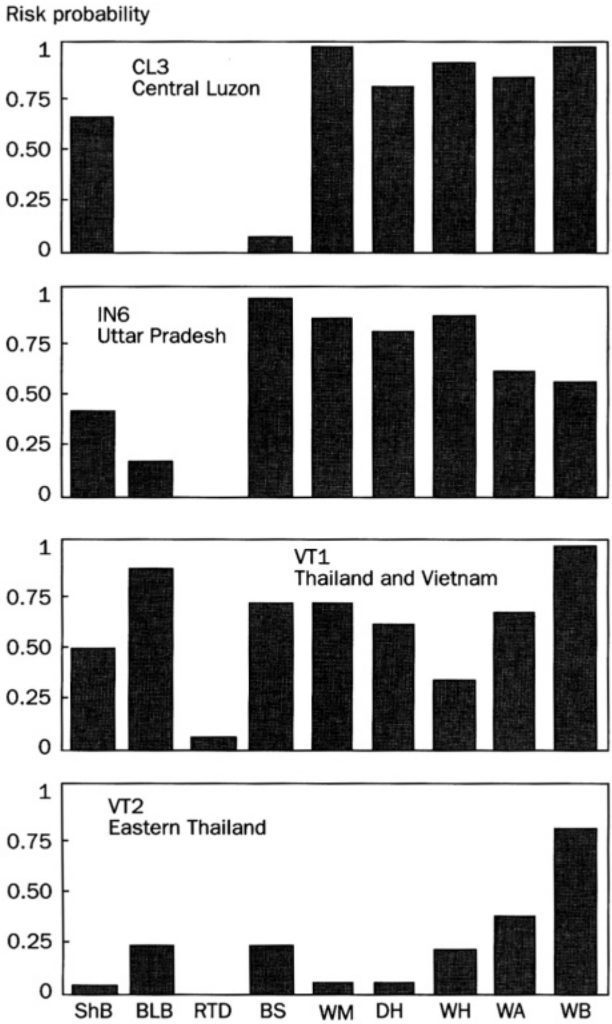



**Fig. 1.** Risk probability: probability of occurrence of nine injuries in selected production situations in four countries. Only four examples are shown. Each histogram represents a particular production situation at a site or in a country (e.g., CL3, Central Luzon). The horizontal axis indicates injuries: ShB = sheath blight, BLB = bacterial leaf blight, RTD = rice tungro disease, BS = brown spot, WM = whorl maggot, DH = deadhearts, WH = whiteheads, WA = weed above the rice crop canopy, WB = weed below the rice crop canopy. The vertical axis indicates the proportion (0 to 1) of affected fields.

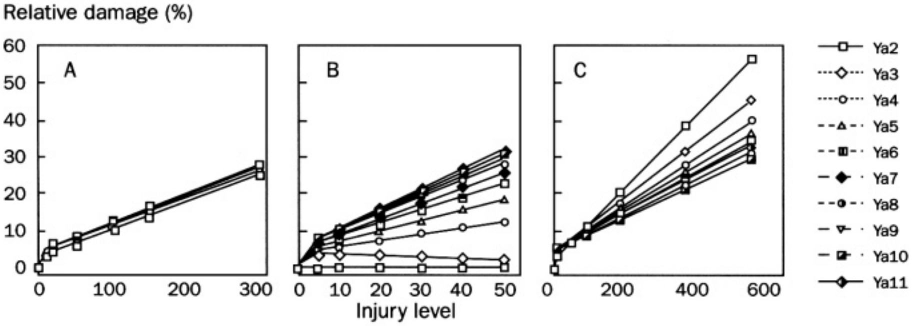



**Fig. 2.** Damage functions for three injuries: weeds above the rice crop canopy, sheath blight injury, and rice tungro disease. (A) Effects of weeds above the crop canopy (area under the disease progress curve in % days). (B) Effects of sheath blight (maximum severity in %). (C) Effects of RTD injury (% area affected × symptom score). Increasing injury levels are indicated on the horizontal axes. Increasing damage is indicated on the vertical axes in relative terms (%). Damage functions are shown for a range of attainable yields, from 2 t $ha^{-1}$ (Ya2) to 11 t $ha^{-1}$ (Ya11).

magnitude were then multiplied by the estimates for risk probabilities in the corresponding production situations (Fig. 2) to produce estimates for risk. Figure 3 shows the considerable variation in risks depending on injuries and production situations.

## Revisiting the concepts of threshold and crop loss profile

The concepts of injury profile (Pinstrup-Andersen et al 1976) and thresholds (Stem 1973) are of central importance to plant protection. In the context of changes in production situations, these concepts need to be adapted to account for variations in attainable yield and allow examination of injury combinations. One useful approach is to consider the yield of a crop as a response surface (Teng and Gaunt 1980). The risk-analytical approach illustrates well, in an empirical way, the fact that changes in production situations must be factored in when setting priorities for pest management. This approach implies the same principles as a systems-analytical one, in which, according to Rabbinge (1993):

- potential yield is defined by factors such as crop genotype, radiation, or temperature;
- potential yield is then limited to an attainable yield by factors such as water and nutrient availability; and
- attainable yield is reduced in turn by factors such as injuries.

Both the systems-analytical (Elings and Rubia 1994) and the risk-analytical approaches are used at IRRI. Their combination might provide a solid empirical basis to model extrapolations.

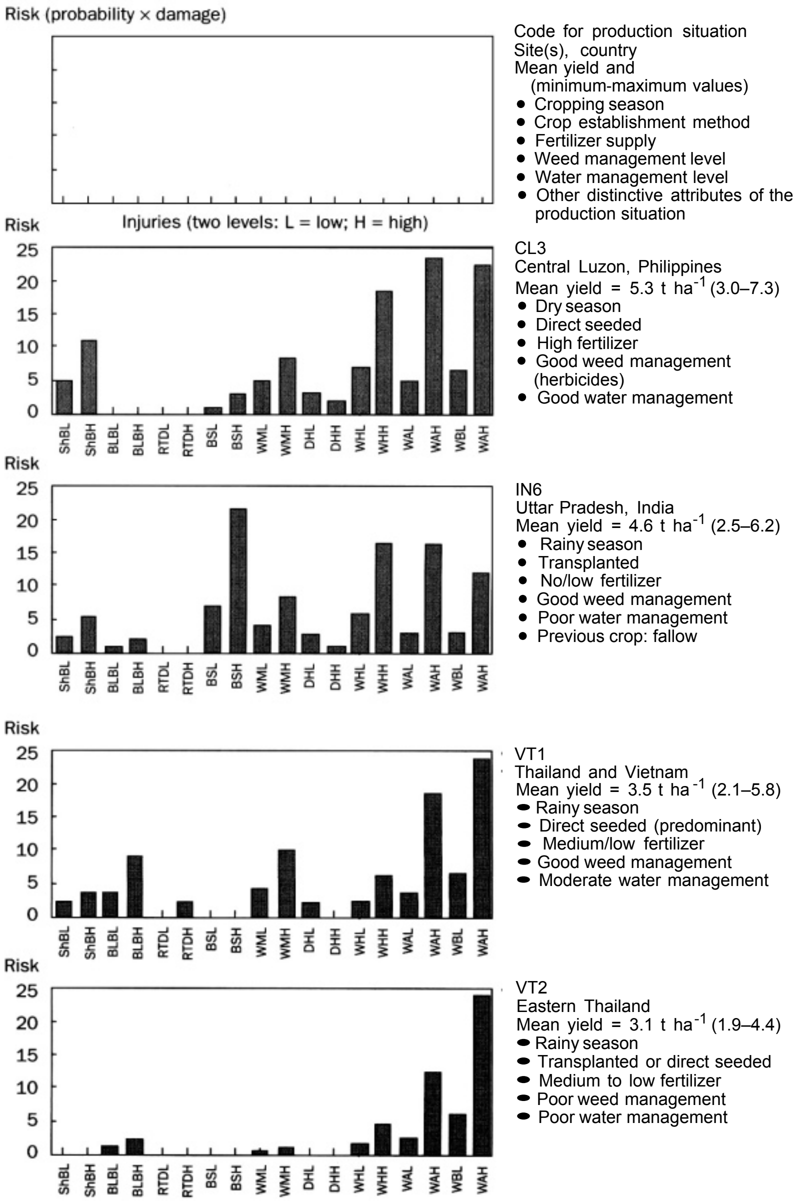



**Fig. 3.** Estimated risk magnitudes in selected production situations in four countries. The horizontal axis indicates injuries caused by ShB (sheath blight), BLB (bacterial leaf blight), RTD (rice tungro disease), BS (brown spot), WM (whorl maggot), DH (deadhearts), WH (whiteheads), WA (weed above the rice crop canopy), and WB (weed below the rice crop canopy). For each injury, two levels, high (H) or low (L), are shown. (Adapted from Savary et al 1997.)

## New directions for host-plant resistance to diseases and insects in rice

For thousands of years, farmers have recognized that some crop varieties produce a larger yield of good quality than other varieties, under conditions of similar insect and pathogen populations and other environmental factors. In the modern discipline of host-plant resistance (HPR), plant breeders, entomologists, and plant pathologists identify genes that confer pest resistance and introduce them into suitable agronomic backgrounds. HPR is a key component of IPM systems in rice and has been a focus of research at IRRI almost since the founding of the institute. Multiple pest resistance has been a feature of IRRI varieties released since the 1960s, and this has made immense contributions to increased and stabilized yields (Khush 1995). The use of rice germplasm as a source of genes for pest resistance is reviewed by Bellon et al elsewhere in this book (Chapter 16). Here we review new approaches to increase the efficiency of breeding for pest resistance, introduce resistance genes from outside the rice gene pool, and enhance the durability of resistant varieties in farmers' fields.

### DNA marker-assisted selection

Marker-assisted selection (MAS) enables plant breeders to improve the efficiency of breeding when an important trait, which is difficult to assess, is tightly linked to a trait that is easily measured. Although the development of molecular biology and DNA-based markers has vastly expanded the potential of MAS in plant breeding, breeders have for many years also used morphological markers. For example, a gene for resistance to brown planthopper (BPH) is closely linked to a gene specifying purple coleoptile color in some traditional rice varieties grown in northeast India. When a resistant plant with a purple coleoptile is crossed with a susceptible plant with a green coleoptile, more than 95% of the $F_2$ plants showing purple coleoptile are also resistant to BPH. In this case, coleoptile color is a morphological marker that is used to help select for BPH resistance.

Unfortunately, few morphological markers are known. They tend to be particular to certain rice varieties, and most morphological markers are mutations that are deleterious to rice plants. A homozygous locus is indistinguishable from a heterozygous one when a dominant allele is involved. Moreover, the usefulness of the approach is limited to traits controlled by single major genes; it does not apply to many agronomically important traits that are governed by many unlinked genes.

The advent of molecular markers has enormously increased the power of MAS. The most commonly used DNA markers are restriction fragment length polymorphism (RFLP) markers. Other kinds of DNA markers have been developed recently. In MAS, target genes are detected based on the genotype as determined by the DNA markers and not on the phenotypic expression of the genes.

Figure 4 illustrates the principle and genetic basis of marker-assisted identification of a target gene. We assume that a locus on a rice chromosome is responsible for a character such as resistance to blast. The donor parent carries a resistance allele (R) linked to a DNA marker allele (m) and the recipient parent carries a susceptible allele

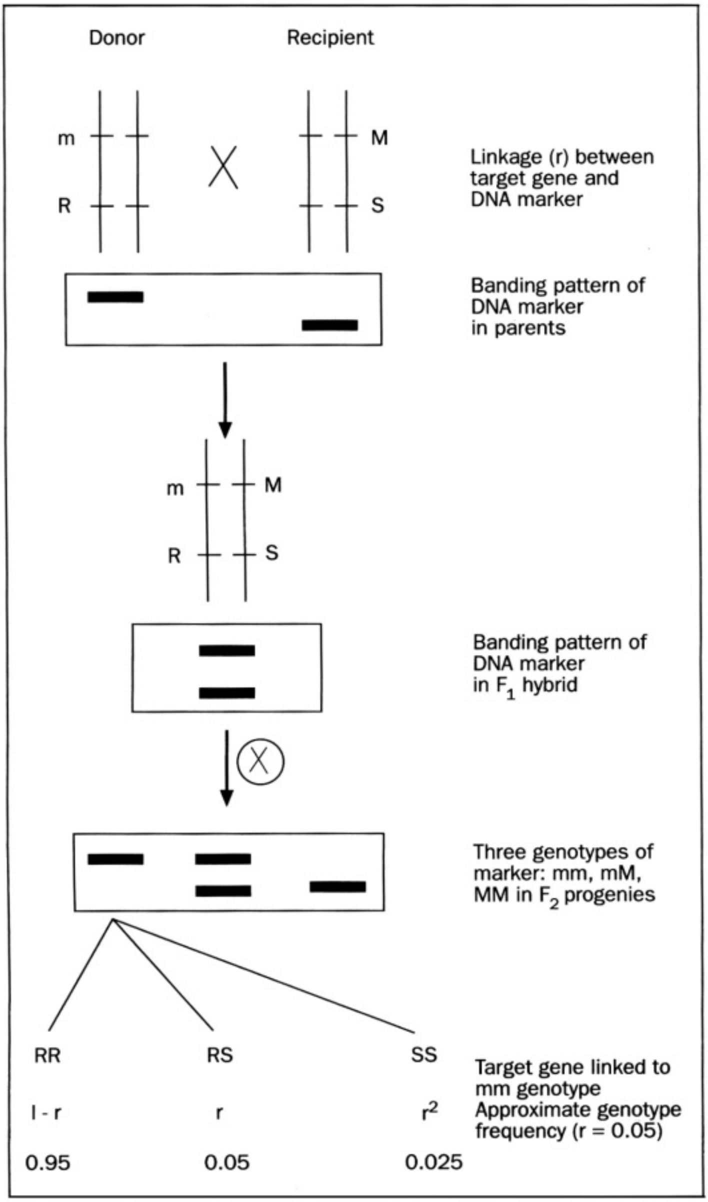



**Fig. 4.** Schematic diagram of genetic basis of marker-assisted selection with codominant DNA markers.

(S) linked to a DNA marker allele (M). The genetic distance between the DNA marker locus and the gene locus is the recombinant frequency (r in Fig. 4, r = 0.05) as determined when the gene was first mapped.

After crossing the donor parent with the recipient, we obtain an $F_1$ hybrid that is heterozygous in both the target resistance gene and the DNA marker locus as indicated by the DNA banding pattern in gel analysis. The selfing of the $F_1$ hybrid produces the segregating $F_2$ population. Based on the banding pattern of DNA markers, individuals of the segregating population can be classified into three groups (MM, Mm, and mm). Within the mm group, the majority of the plants carry the resistance allele (R) because of linkage. The smaller the r value (the distance between the marker and target gene), the higher the proportion of the plants in the mm group carrying the R allele. Therefore, selection based on the DNA marker permits selection of the target gene unless the selected individual carries a recombinant chromosome. If the recombination frequency between the DNA marker and the target gene does not change from gene mapping population to breeding population, a relation discussed later, we would be able to select the target gene based on the DNA marker with a predictable rate of accuracy.

The MAS technique has many advantages in rice breeding in that it can be used at any time and at any growth stage of rice. This advantage is obvious when there are two or three breeding seasons in a year, but the pest can only be collected and analyzed once a year. Selection of minor genes (quantitative trait loci) is difficult with the conventional approach because of epistasis of gene actions and environmental effect. Identification of target genes by markers can avoid these problems. IRRI's success in using MAS to pyramid genes for bacterial blight (BB) resistance demonstrates the power of MAS in improving breeding efficiency.

Bacterial blight caused by *Xanthomonas oryzae* pv. *oryzae* is one of the most destructive diseases of rice throughout the world, but has been successfully controlled in many areas through the deployment of resistant varieties (Khush et al 1989). Nineteen rice genes conferring resistance to BB have been identified (Kinoshita 1995), several of which have been incorporated into modern rice varieties. The *Xa-4* gene has been of particular importance, but large-scale and long-term cultivation of varieties carrying *Xa-4* in Indonesia, India, China, and the Philippines has led to a significant shift of the dominant BB host races in these countries (Mew et al 1992). In many areas, rice varieties with *Xa-4* have become susceptible to BB. One way to delay such a breakdown in BB resistance is to pyramid multiple resistance genes into rice varieties. This method, however, can be difficult or impossible with a conventional approach because of epistasis of gene actions, particularly when a breeding line already carries a gene such as *Xa-21,* which shows resistance to all BB races when the varieties are being developed. With a conventional approach, a breeding line with *Xa-21* only cannot be distinguished from a breeding line with *Xa-21* plus some other genes.

DNA markers were used to assist in the pyramiding of four BB resistance genes (Huang et al 1997). All possible combinations of the four resistance genes were obtained (Table 1). The pyramided lines show a wider spectrum or higher level of resis-

**Table 1. Plants containing two or more bacterial blight resistance genes were selected based on DNA marker analysis (modified from Huang et al 1997).**

| Lines | Gene combinations | Race | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| IRBB4 | *Xa-4* | R[a] | S | S | S | R | S |
| IRBB5 | *xa-5* | R | R | R | MS | R | S |
| IR66999-1-1-5-2 | *xa-13* | S | S | S | S | S | R |
| IR66700-3-3-3-4-2 | *Xa-21* | R | R | R | R | R | R |
| IR24 | – | S | S | S | S | S | S |
| IRBB50 | *Xa-4/xa-5* | R+ | R | R | R | R+ | S |
| IRBB51-1 | *Xa-4/xa-13* | R | S | S | R | R | R |
| IRBB51-2 | *Xa-4/xa-13* | R | S | S | R | R | R |
| IRBB51-3 | *Xa-4/xa-13* | R | S | S | R | R | R |
| IRBB51-4 | *Xa-4/xa-13* | R | S | S | R | R | R |
| IRBB52 | *Xa-4/Xa-21* | R+ | R | R | R | R+ | R |
| IRBB53-1 | *xa-5/xa-13* | R | R | R | R | R | R |
| IRBB53-2 | *xa-5/xa-13* | R | R | R | R | R | R |
| IRBB53-3 | *xa-5/xa-13* | R | R | R | R | R | R |
| IRBB53-4 | *xa-5/xa-13* | R | R | R | R | R | R |
| IRBB54-1 | *xa-5/Xa-21* | R+ | R+ | R+ | R | R+ | R |
| IRBB54-2 | *xa-5/Xa-21* | R+ | R+ | R+ | R | R+ | R |
| IRBB54-3 | *xa-5/Xa-21* | R+ | R+ | R+ | R | R+ | R |
| IRBB55-1 | *xa-13/Xa-21* | R | R | R | R | R | R |
| IRBB55-2 | *xa-13/Xa-21* | R | R | R | R | R | R |
| IRBB55-3 | *Xa-21/xa-13* | R | R | R | R | R | R |
| IRBB55-4 | *xa-13/Xa-21* | R | R | R | R | R | R |
| IRBB56-1 | *Xa-4/xa-S/xa-13* | R+ | R | R | R+ | R+ | R |
| IRBB56-2 | *Xa-4/xa-5/xa-13* | R+ | R | R | R+ | R+ | R |
| IRBB57-1 | *Xa-4/xa-5/Xa-21* | R+ | R+ | R+ | R+ | R+ | R |
| IRBB57-2 | *Xa-4/xa-5/Xa-21* | R+ | R+ | R+ | R+ | R+ | R |
| IRBB57-3 | *Xa-4/xa-5/Xa-21* | R+ | R+ | R+ | R+ | R+ | R |
| IRBB58-1 | *Xa-4/xa-13/Xa-21* | R+ | R | R | R+ | R+ | R |
| IRBB58-2 | *Xa-4/xa-13/Xa-21* | R+ | R | R | R+ | R+ | R |
| IRBB58-3 | *Xa-4/xa-13/xa-21* | R+ | R | R | R+ | R+ | R |
| IRBB59-1 | *xa-5/xa-13/Xa-21* | R+ | R+ | R+ | R+ | R+ | R |
| IRBB59-2 | *xa-5/xa-13/Xa-21* | R+ | R+ | R+ | R+ | R+ | R |
| IRBB59-3 | *xa-5/xa-13/Xa-21* | R+ | R+ | R+ | R+ | R+ | R |
| IRBB60-1 | *Xa-4/xa-5/xa-13/Xa-21* | R+ | R+ | R+ | R+ | R+ | R |
| IRBB60-2 | *Xa-4/xa-5/xa-13/Xa-21* | R+ | R+ | R+ | R+ | R+ | R |

[a] R = resistant, S = susceptible, MS = moderately susceptible, R+ = highly resistant.

tance to the bacterial pathogen. This effect can be seen from the pyramided lines carrying *xa-4/xa-13.* The variety IRBB4, carrying *Xa-4,* was resistant to races 1 and 5 but susceptible to other races. On the other hand, IR66699, carrying *xa-13,* was resistant to race 6 only. The lines with both *Xa-4* and *xa-13* showed resistance to races 1, 5, and 6 as did their parents. Furthermore, these pyramided lines showed resistance to race 4, which can infect both parents (IRBB4 and IR66699).

## Rice transformation

Although techniques such as embryo rescue have widened the pool of germplasm available for improvement of cultivated rice, several important insects and diseases remain for which sources of resistance have not been found in the genus *Oryza.* Among these pests are ShB and the complex of caterpillar pests known as stem borers. Even for genes that occur in the rice gene pool, plant transformation may be preferable to conventional backcrossing of resistance genes into elite cultivars, for example, by allowing the genes to be introduced without disrupting complex genetic traits such as grain quality, or by increasing the level of expression of existing resistance genes. These applications of genetic engineering can be illustrated by recent achievements in resistance to ShB, BB, and stem borers.

Lin et al (1995) transformed the indica variety Chinsurah Boro II with a rice chitinase gene. The transgenic plants express the chitinase gene constitutively, rather than only after fungal infection of the plant has taken place, as do normal rice plants. In greenhouse tests, the transgenic plants show enhanced resistance to the ShB pathogen, *Rhizoctonia solani.* Song et al (1995) cloned a gene conferring resistance to another rice disease, BB, from an African species of wild rice, *Oryza longistaminata.* This gene, *Xa-21,* has been shown to confer resistance to BB when genetically engineered into IR64 (Song et al 1995) and IR72 (Tu et al 1998). Several rice varieties have now been transformed with toxin genes from *Bacillus thuringiensis* (*Bt*), and been shown to have enhanced resistance to stem borers (e.g., Fujimoto et al 1993, Wunn et al 1996, Ghareyazie et al 1997, Wu et al 1997, Datta et al 1998). The production of these initial transgenic lines has been important in demonstrating that the foreign gene "constructs" used in their transformation can function well in rice. Larger numbers of transgenic lines are now being produced at IRRI and numerous other institutions, and are being screened in containment greenhouses to identify those that perform best. Some of the best lines will eventually be evaluated under field conditions. Field tests of transgenic rice have already begun in China, and by the year 2000 field tests will likely be under way in several other Asian countries.

Three methods have been used successfully for rice transformation (Fig. 5): protoplast transformation, particle bombardment, and *Agrobacterium*-mediated transformation. Protoplasts are plant cells freed of their cell wall by enzymatic digestion. Protoplasts can uptake foreign DNA after treatment with polyethylene glycol, a neutral polymer, or application of an electric current in a process known as electroporation. In the biolistic method, also known as particle bombardment, DNA associated with tiny gold particles is shot into cells with a burst of high pressure. *Agrobacterium*-mediated transformation makes use of a species of plant parasitic bacterium, *Agrobacterium tumefaciens,* that harbors a virus capable of inserting its DNA into plant chromosomes. Progress in the efficiency of transformation and tissue culture regeneration is still needed, particularly for indica varieties.

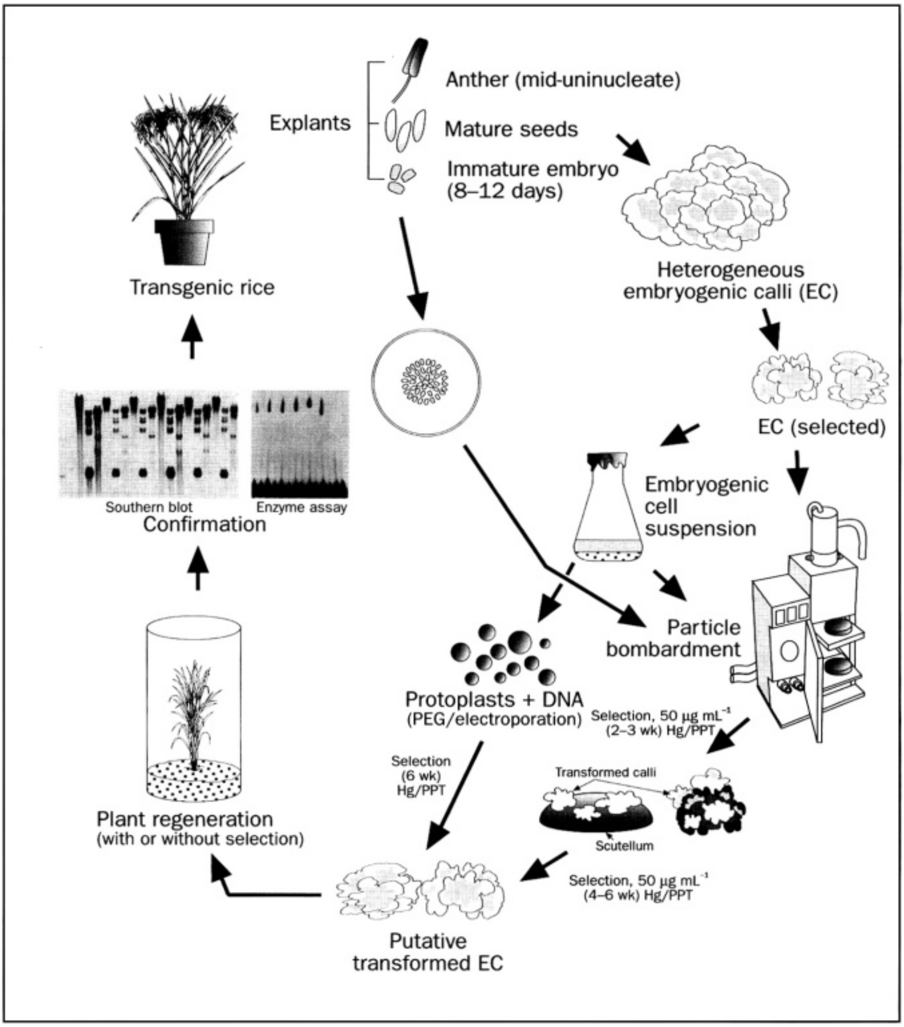



**Fig. 5.** Protocol for production of fertile transgenic rice plants using biolistic and protoplast systems. (Modified after Datta 1995.)

## Sustainable deployment of pest-resistant rice cultivars

Plant pathogens and insect pests have demonstrated an impressive capacity to adapt to resistant cultivars. In addition to the inherent genetic potential of pests to respond to selection imposed by resistance genes, the "breakdown" of resistance in many rice varieties has been accelerated by the release of cultivars containing simple genetic resistance backgrounds (often a single major gene for each target pest) and by the deployment of some of these cultivars as monocultures over vast areas. Resistance breakdown has led to episodes of yield instability and to a continuing need to identify new resistance genes and incorporate them into new varieties. Novel approaches to improve the durability of resistance to insects and diseases are being pursued at IRRI, and are as relevant to genetically engineered cultivars as they are to conventional ones. These approaches include increasing the genetic complexity of resistance to particular pests and the strategic deployment of cultivars in farmers' fields.

*Diseases.* With advances in molecular genetics, new tools have become available to better understand and deploy resistance genes for rice diseases (McCouch et al 1988, Hamer 1991, Leach et al 1992). One new approach relies on analyzing the genetics of resistance in traditional cultivars that have demonstrated durable resistance in farmers' fields and identifying "gene tags" that can be used to incorporate resistance from such cultivars into modern varieties. This information can lead to the strategic deployment of a diversity of resistance genes either within fields or among fields, as an alternative to the large-scale cultivation of varieties with single resistance genes. Tagging resistance genes permits us to develop sets of near-isogenic lines (NILs) in which different resistance genes are introduced into a common genetic background. This allows us to characterize individual genes and to pyramid them (based on the spectrum of their resistance to various pathogen populations) in a marker-assisted breeding program (Table 1) or release the NILs as multilines (mixtures of cultivars that are genetically similar except for their disease resistance genes). Varietal mixtures have been deployed successfully in various crop systems (Wolfe 1985, Schaffner et al 1992).

Analysis of the genetic basis of durable resistance to the blast fungus (*Pyricularia grisea*) in Moroberekan, a traditional West African upland rice cultivar, showed that the resistance consists of multiple major and minor genes (Mackill and Bonman 1992). Characterization of these genes from recombinant inbred populations led to the production of NILs that carry them separately (Wang et al 1994). These NILs are now being used to dissect the effects of major and minor genes for disease resistance and to evaluate the intrafield diversification deployment strategy to control rice blast (Chen, Zeigler, and Nelson, unpublished data). In the upland rice ecosystem, planting mixtures of rice cultivars in a field has been a traditional practice (Bonman et al 1986).

Durable resistance to BB in China, Indonesia, and the Philippines has also been attributed to a complex (quantitative) resistance in traditional cultivars (Lee et al 1989, Mew et al 1992). The availability of NILS for BB (Ogawa 1993, Ikeda et al 1990) has allowed scientists to further characterize these genes and to identify gene tags that are useful for selection in a breeding program (Yoshimura et al 1995, McCouch et al 1991, Ronald et al 1992). Further testing of the spectrum of resistance for each of the identified resistance genes has helped researchers design a more targeted combination of genes in a pyramid breeding line.

Experiments were conducted in farmers' fields in the Philippines to evaluate the deployment of nine varietal combinations that included various resistance backgrounds to BB (pure stands, two-component mixtures, and two-gene pyramids). Initial results showed that both pyramids and partial resistance from "broken down" major genes reduced BB severity (Ahmed et al 1997).

Cultivars with durable sources of resistance to blast and BB have been identified and the genetic basis of their durability is being studied. But no durable resistance has been reported for RTD. Most of the deployed cultivars carry a major gene for resistance to the vector, green leafhoppers. Breeding for resistance to RTD is further complicated by the fact that the disease is caused by two viruses—rice tungro spherical virus (RTSV) and rice tungro bacilliform virus (RTBV)—and one of them (RTBV) depends on the other for its transmission. Several NILs, carrying genes for resistance to the spherical virus, have been developed and are being characterized (Sebastian et al 1996, Ikeda and Imbe, unpublished data). Because RTBV transmission depends on RTSV, it has been difficult to screen for resistance to RTBV. Dasgupta et al (1991), however, showed that the cloned RTVB-G, strain can be singly inoculated into rice using agroinfection. This technique was used to confirm the previously identified tolerance (Ikeda and Imbe, unpublished data) in Utri Merah and Balimau Putih to RTBV (Dahal et al 1992, Sta Cruz and Assam, unpublished). Durable resistance depends not only on the inherent properties of the resistance in a cultivar but also on how and where the cultivar is grown. In South Sulawesi, Indonesia, genetic resistance to the vector of rice tungro viruses works in concert with appropriate planting time and other cultural practices for RTD management (Sama et al 1991).

*Insects.* In 1996, farmers in the United States became the first to begin commercial production of crops genetically engineered with insecticidal toxins from the bacterium *Bacillus thuringiensis* (*Bt*). Large numbers of "*Bt* rice" lines are under evaluation in containment greenhouse facilities at IRRI and other institutions, and small-scale field tests of some lines began in China in 1997 (Ye Gongyin, Zhejiang Agricultural University, personal communication). Once lines are identified that perform well in small-scale field tests, more multisite testing will probably be required by national seed boards, as is the case for all new varieties. Thus, it will be several years before *Bt* rice becomes available to farmers. The important potential benefits of *Bt* rice include reduced yield losses to stem-boring caterpillars and a reduction in chemical insecticide applications against these pests. But *Bt* toxins are insecticides and, like conventional chemical insecticides, insects may quickly adapt to them unless *Bt* plants are carefully designed and deployed. With the recent development and release of *Bt* crops, "resistance management" for transgenic insect-resistant crops has become a very active area of research (Gould 1996, 1998).

One strategy that has been much discussed is combining two or more genes for insect resistance within a single cultivar. With almost 100 kinds of *Bt* toxins having been identified (Schnepf 1995), this at first seemed a promising approach for *Bt* crops. Because insects that carry mutations conferring resistance to a novel toxin are relatively rare when the toxins are first deployed, it seems reasonable to assume that insects resistant to two novel toxins will be much rarer. But toxin combinations will enhance durability only if mutations conferring resistance to one toxin do not confer resistance to the second, and it is now known that some insect mutations can confer resistance to even highly divergent kinds of *Bt* toxins (Gould et al 1992). A greater assurance of durable resistance can be achieved if a *Bt* toxin is combined with a second, unrelated type of toxin. Consequently, there has been a great deal of private- and public-sector research on identifying toxins with the desirable characteristics of *Bt* toxins, such as high effectiveness against insect pests at low doses and an absence of mammalian toxicity. Some promising new toxins have been identified (Carozzi and Koziel 1997).

Whether transgenic insect-resistant plants contain one toxin or multiple toxins, it is known that insect resistance to the toxins can be slowed by the use of refuges. Refuges are periods of time or areas of space in which a toxin is not used and they serve to maintain toxin-susceptible insects in local populations. Because alleles that confer insecticide resistance are generally recessive, mating between resistant and susceptible insects usually produces susceptible progeny. Temporal refuges can be established by rotating varieties or using gene "promoters" that drive the expression of toxin genes only at certain stages of plant growth, for example, at the reproductive stage but not at the vegetative stage. Spatial refuges can be established within fields by sowing mixtures containing seeds of toxic and nontoxic plants, or among fields by planting some fields to nontoxic plants. Which spatial scale is most effective is highly dependent on the biology of the target pest species. Studies of important aspects of rice stem borer biology, such as larval movement among plants and dispersal of adult insects among fields, are under way at IRRI (Cohen et al 1996). In the United States, Monsanto requires all farmers growing their "Bollgard" *Bt* cotton to plant a proportion of their land to non-*Bt* cotton, to serve as a refuge. It will not be possible to maintain refuges in this way for *Bt* rice in Asia, where there are hundreds of millions of small farmers. It remains to be seen whether a sufficient level of "unstructured refuges," arising as a result of some farmers growing non-*Bt* rice varieties by preference or by chance, will be maintained in rice-growing areas. The amount of refuge area required will be lower if two toxins are used, because insects having resistance to both toxins will be rare. Thus, the use of multiple toxins may be particularly important for sustainable use of transgenic insect-resistant rice varieties.

## References

Ahmed HU, Finckh MR, Alfonso RF, Mundt CC. 1997. Epidemiological effect of gene deployment strategies on bacterial blight of rice. Phytopathology 87:66-70.

Bonman JM, Estrada BA, Denton RI. 1986. Blast management with upland rice cultivar mixtures. In: Proceedings of the Symposium on Progress in Upland Rice Research, Los Baños, Laguna. Manila (Philippines): International Rice Research Institute. p 375-382.

Carozzi N, Koziel M, editors. 1997. Advances in insect control: the role of transgenic plants. London (UK): Taylor & Francis.

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 Oct 1995. Manila (Philippines): International Rice Research Institute. p 749-752.

Dahal G, Dasgupta I, Lee G, Hull R. 1992. Comparative transmission of three tungro isolates by green leafhopper (GLH). Int. Rice Res. Notes 17:3.

Dasgupta I, Hull R, Eastop S, Pogi-Pollini C, Blakebrough M, Boulton MI, Davies JW. 1991. Rice tungro bacilliform virus DNA independently infects rice after *Agrobacterium*-mediated transfer. J. Gen. Virol. 72:1215-1221.

Datta SK. 1995. Polyethylene glycol mediated direct gene transfer to indica rice protoplast and regeneration of transgenic plants. In: Potrykus I, Spangenberg G, editors. Gene transfer in plants. Berlin (Germany): Springer Pub. p 66-74.

Datta K, Vasquez A, Tu J, Torrizo L, Alam MF, Oliva N, Abrigo E, Khush GS, Datta SK. 1998. Constitutive and tissue-specific differential expression of *cryIA(b)* gene in transgenic rice plants conferring resistance to rice insect pests. Theor. Appl. Genet. (In press.)

De Wit CT. 1982. La productivité des pâturages sahéliens. In: Penning de Vries FWT, Djiteye MA, editors. La Productivité des Pâturages Sahéliens - Une Etude des Sols, des Végétations et de l'Exploitation de cette Ressource Naturelle. Pudoc, Wageningen, Netherlands. p 22-35.

Elazegui FA, Soriano J, Bandong J, Estorninos L, Jonson I, Teng PS, Shepard BM, Litsinger JA, Moody K, Hibino H. 1990. Methodology used in the IRRI integrated pest survey. In: Crop loss assessment in rice. Manila (Philippines): International Rice Research Institute. p 243-271.

Elings A, Rubia EG, editors. 1994. Analysis of damage mechanisms by pests and diseases and their effects on rice yield. SARP Research Proceedings. DLO (Wageningen): Wageningen Agricultural University and Manila (Philippines): International Rice Research Institute. 279 p.

Fujimoto H, Itoh K, Yamamoto M, Kyozuka J, Shimamoto K. 1993. Insect resistant rice generated by introduction of a modified δ-endotoxin gene of *Bacillus thuringiensis.* Biotechnology 11:1151-1155.

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

Gould F. 1996. Deploying pesticidal engineered crops in developing countries. In: Persley GJ, editor. Biotechnology and integrated pest management. Wallingford (UK): CAB International. p 264-293.

Gould F. 1998. Sustainability of transgenic insecticidal cultivars: integrating pest genetics and ecology. Annu. Rev. Entomol. 43:701-726.

Gould F, Martinez-Ramirez A, Anderson A, Ferre J, Silva FJ, Moar WJ. 1992. Broad spectrum resistance to *Bacillus thuringiensis* toxins in *Heliothis virescens.* Proc. Nat'l. Acad. Sci. USA 89:7986-7990.

Hamer JE. 1991. Molecular probes for rice blast disease. Science 252:632-633.

Huang N, Angeles ER, Domingo J, Magpantagy G, Singh S, Zhang G, Kumaravadivel N, Bennett J, Khush GS. 1997. Pyramiding of bacterial blight resistance genes in rice: marker-assisted selection using RFLP and PCR. Theor. Appl. Genet. 95:313-320.

Ikeda R, Khush GS, Tabien RE. 1990. A new resistance gene to bacterial blight derived from *O. longistaminata.* Jpn. J. Breed. 40:280-281.

IRRI (International Rice Research Institute). 1994. Integrated pest management: the IRRI perspective. IRRI Information Series No. 3. Manila (Philippines): IRRI. 20 p.

James CW. 1974. Assessment of plant diseases and losses. Annu. Rev. Phytopathol. 12:27-48.

Khush GS. 1984. Terminology for rice growing environments. Manila (Philippines): International Rice Research Institute.
Khush GS. 1995. Moderm varieties: their real contribution to food supply and equity. GeoJournal 35:275-284.
Khush GS, Mackill DJ, Sidhu GS. 1989. Breeding rice for resistance to bacterial blight. In: Bacterial blight of rice. Manila (Philippines): International Rice Research Institute. p 207-217.
Kinoshita T. 1995. Report of Committee on Gene Symbolization, Nomenclature, and Linkage Groups. Rice Genet. Newsl. 12:9-153.
Leach JE, Rhodes ML, Vera Cruz CM, White FF, Mew TW, Leung H. 1992. Assessment of genetic diversity and population structure of *Xanthomonas oryzae* pv. *oryzae* with a repetitive DNA element. Appl. Environ. Microbiol. 58:2188-2195.
Lee EJ, Zhang Q, Mew TW. 1989. Progress in irrigated rice research. Manila (Philippines): International Rice Research Institute.
Lin W, Anuratha CS, Datta K, Potrykus I, Muthukrishnan S, Datta S. 1995. Genetic engineering of rice for resistance to sheath blight. Bio/Technology 13:686-691.
Mackill DJ, Bonman JM. 1992. Inheritance of blast resistance in near-isogenic lines of rice. Phytopathology 82:746-749.
Madden LV. 1983. Measuring and modeling crop losses at the field level. Phytopathology 73: 1591-1596.
McCouch SR, Abenes ML, Angeles R, Khush GS, Tanksley SD. 1991. Molecular tagging of a recessive gene, *xa-5,* for resistance to bacterial blight of rice. Rice Genet. Newsl. 8:143-145.
McCouch SR, Kochert G, Yu ZH, Wang ZY, Khush GS, Coffman WR, Tanksley SD. 1988. Molecular mapping of rice chromosomes. Theor. Appl. Genet. 76:815-829.
Mew TW, Vera Cmz CM, Medalla ES. 1992. Changes in race frequency of *Xanthomonas oryzae* pv. *oryzae* in response to rice cultivars planted in the Philippines. Plant Dis. 76:1029-1032.
Ogawa T. 1993. Methods and strategy of monitoring race distribution and identification of resistance genes to bacterial blight (*Xanthomonas oryzae* pv. *oryzae*) in rice. JARQ 27:71-80.
Pingali PL, Roger PA, editors. 1995. Impact of pesticides on farmer health and the rice environment. Manila (Philippines): International Rice Research Institute.
Pinnschmidt HO, Nguyen Dan Long, Tran Tan Viet, Le Dinh Don, Teng PS. 1995. Characterization of pests, pest losses, and production patterns in rainfed lowland rice of the Mekong River Delta. In: Denning GL, Vo-Tong Xuan, editors. Vietnam and IRRI: a partnership in rice research. (Manila) Philippines: International Rice Research Institute. p 223-242.
Pinstrup-Andersen P, de Londono N, Infante M. 1976. A suggested procedure for estimating yield and production losses in crops. PANS 22:359-365.
Rabbinge R. 1993. The ecological background of food production. In: Crop protection and sustainable agriculture. Ciba Foundation Symposium 177. Chichester: John Wiley and Sons. p 2-29.
Ronald PC, Albano B, Tabien R, Abenes L, Wu K, McCouch S, Tanksley S. 1992. Genetic and physical mapping of the rice bacterial blight resistance locus *Xa-21*. Mol. Gen. Genet. 236:113-120.
Rowe WD. 1980. Risk assessment approaches and methods. In: Conran G, editor. Society, technology, and risk assessment. New York: Academic Press. p 3-29.

Sama S, Hasanuddin A, Manwan I, Cabunagan R, Hibino H. 1991. Integrated management of rice tungro disease in South Sulawesi (Indonesia). Crop Prot. 10:34-40.

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

Savary S, Elazegui FA, Pinnschmidt, Teng PS. 1997. Characterization of rice pest constraints in Asia: an empirical approach. In: Teng PS, Kropff M, ten Berge HFM, Dent JB, Lansigan FP, van Laar HH, editors. Systems approaches for agricultural development. Vol. I. Dordecht: Kluwer. p 83-98.

Schaffner D, Koller B, Mueller K, Wolfe MS. 1992. Response of populations of *Erysiphe graminis* sp. *hordei* to large-scale use of variety mixtures. Vortraege fuer Pflanzenzuechtung 24:317-319.

Schnepf HE. 1995. *Bacillus thuringiensis* toxins: regulation, activities and structural diversity. Current Opinion Biotechnol. 6:305-312.

Sebastian LS, Ikeda R, Huang N, Imbe T, Coffman WR, McCouch SR. 1996. Molecular mapping of resistance to rice tungro spherical virus and green leafhopper. Phytopathology 86:25-30.

Song W-Y, Wang G-L, Chen L-L, Kim H-S, Pi L-Y, Holsten T, Gardner J. Wang B, Zhai W-X, Zhu L-H, Fauquet C, Ronald P. 1995. A receptor kinase-like protein encoded by the rice disease gene, *Xa-21.* Science 270:1804-1806.

Stem VM. 1973. Economic thresholds. Annu. Rev. Entomol. 18:259-280.

Teng PS. 1983. Estimating and interpreting disease intensity and loss in commercial fields. Phytopathology 73:1587-1590.

Teng PS, Gaunt RE. 1980. Modeling systems of disease and yield loss in cereals. Agric. Syst. 6:131-154.

Teng PS, Savary S. 1992. Implementing the systems approach in pest management. Agric. Syst. 40:237-264.

Tu J, Isabelida O, Zhang Q, Mew TW, Khush GS, Datta SK. 1998. Transgenic rice variety IR72 with *Xa-21* is resistant to bacterial blight. Theor. Appl. Genet. (In press.)

Waage J. 1996. Integrated pest management and biotechnology: an analysis of their potential for integration. In: Persley GJ, editor. Biotechnology and integrated pest management. Wallingford (UK): CAB International. p 37-60.

Wang G, Mackill DJ, Bonman JM, McCouch SR, Nelson RJ. 1994. RFLP mapping of genes conferring complete and partial resistance to blast resistance 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 rice—a review. Bull. Entomol. Res. 84:567-587.

Wolfe MS. 1985. The current status and prospects of multiline cultivars and variety mixtures for disease resistance. Annu. Rev. Phytopathol. 23:251-273.

Wu C, Fan Y, Zhang C. Oliva N, Datta SK. 1997. Transgenic fertile japonica rice plants expressing a modified *cryIA(b)* gene resistant to yellow stem borer. Plant Cell Rep. 17:129-132.

Wunn JA, Kloti A, Burkhardt PK, Ghosh Biswas GC, Launis K, Inglesias VA, Potrykus I. 1996. Transgenic indica rice breeding line IR58 expressing a synthetic *cryIA(b)* gene from *Bacillus thuringiensis* provides effective insect pest control. Bio/Technology 14:171-176.

Yoshimura S, Yoshimura A, McCouch SR, Baraoidan MR, Mew TW, Iwata N, Nelson RJ. 1995. Tagging and combining bacterial blight resistance genes in rice using RAPD and RFLP markers. Mol. Breed. 1:375-387.

Zadoks JC. 1967. Types of losses caused by plant diseases. In: FAO papers presented at the symposium on crop losses. Rome: Food and Agriculture Organization. p 149-158.
Zadoks JC. 1985. On the conceptual basis of crop loss assessment: the threshold theory. Annu. Rev. Phytopathol. 23:455-473.
Zadoks JC, Schein RD. 1979. Epidemiology and plant disease management. New York: Oxford University Press. 427 p.

## Notes

*Authors' addresses:* M. Cohen, S. Savary, O. Azzam, and S.K. Datta, International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines. N. Huang, Applied Phytologics, Inc., 4110 N. Freeway Blvd., Sacramento, CA 95834. USA. m.cohen@cgnet.com s.savary@cgnet.com o.azzam@cgnet.com s.datta@cgnet.com Huang@apinc.com
*Citation:* Dowling NG, Greenfield SM, Fischer KS, editors. 1998. Sustainability of rice in the global food system. Davis, Calif. (USA): Pacific Basin Study Center, and Manila (Philippines): International Rice Research Institute.

CHAPTER 10

# Weeds: a looming problem in modern rice production

M. Olofsdotter, A. Watson, and C. Piggin

Weeds are a constant problem in all rice-growing areas. The reduced availability of water and labor is the driving force that changes cultural practices in rice production. The shift from transplanted to direct seeding of rice aggravates the problem because weeds and the crop emerge together and it is more difficult to use early flooding for weed control. Herbicide use is increasing in Asia because herbicides are cheaper than hand labor and easy to apply. Herbicides have negative effects, however, such as changes in weed flora that result in the increase of hard-to-control weed species, environmental contamination, and selection for herbicide-tolerant weed biotypes. Thus, it is becoming increasingly important to develop integrated weed management systems in which several control measures are combined and herbicide use is minimized. More tools are therefore required to complement good agronomic practices. IRRI research has shown that allelopathy and biological control have the potential to increase weed control. Some rice cultivars can suppress weed growth by more than 50% under field conditions. Research on biological control shows promising results for controlling some of the major weeds in rice.

Rice production must increase from 500 to 800 million t in the next 25 yr to meet projected world rice demand. In addition, this increase must be sought through sustainable agricultural practices to ensure a long-term food supply. Rice production systems are changing rapidly in response to the declining availability of labor and water in rural areas. Direct seeding is being used increasingly to reduce dependence on labor for transplanting. Agrochemicals are also used more frequently to reduce losses from weeds that have traditionally been controlled by flooding. These changes in cultural practices are bringing new selection pressures for weeds and a need to develop better systems of integrated and sustainable weed management.

## Weed management

Weeds are the major biological constraint in most rice-growing areas of the world. Unlike the periodic outbreaks of insect pests and plant diseases, weeds are ever-present and threatening. Problems associated with weeds in rice are mounting dramatically in South and Southeast Asia because of the reduced availability of affordable labor, decreased availability of adequate irrigation water, and the shift in crop establishment from transplanting to direct seeding. The lack of suitable weed control alternatives has led to a reliance on herbicides in many rice-producing areas, and their use is increasing.

Herbicides are generally less expensive than manual labor, very effective, and easy to use. These desirable features, however, are major disincentives to the development of alternative control strategies. The shift to direct seeding has been accompanied by the widespread use of herbicides and has led to a shift from relatively easy-to-control broadleaf weeds to more difficult-to-control grass weeds, especially weedy rice. The continuous use of herbicides naturally selects for tolerant species, leading to the development of herbicide-resistant weeds. Increased herbicide use also poses a threat to human health and the environment.

Our challenge is to create an environment favorable to the rice crop and unfavorable to weeds, where minimal labor, water, and chemical herbicide inputs are required for weed control.

## Integrated weed management

No single weed-management strategy will solve all weed problems in rice (Hill et al 1994). Preventive, physical, managerial, biological, and chemical control methods need to be combined to attain acceptable weed management with minimal use of herbicides (Watson 1992). Integrated weed management emphasizes managing the weed population rather than eradicating weeds (Altieri 1987, Kropff and Moody 1992). Table 1 illustrates this shift from weed control to weed management, which develops

**Table 1. Differences between weed control and weed management.**

| Structure | Weed control | Weed management |
|---|---|---|
| Goal | Maximize crop yield and profits. | Optimize long-term farm productivity. |
| Objectives | Eradicate weeds from the crop. | Maintain weeds below level of significant competition with the crop. |
| Approach | Use one or two of the easiest, most effective methods suited to the crop. | Balance the best available methods suited to the farming system. |
| Action | Employ full-tillage technology, apply full rates of herbicides. | Employ minimum tillage, minimum effective rates of herbicide, and integrated agronomic practices to increase competitive ability of the crop. |
| Outputs | Near-perfect weed elimination, high crop yield. | Substantial reduction of weed pressure, optimum farm profit. |
| Application | Wide geographical regions. | Adapted to specific locations/areas. |

Source: Kon (1993).

long-term strategies to minimize problems caused by weeds in the farming system. Long-term decision making in much of the developing world, however, is constrained because day-to-day issues determine the survival of most subsistence farmers and, understandably, short-term strategies with immediate benefits often prevail (Kon 1993).

## Changes in weed flora

Changes in cultural practices associated with rice production contribute to changing the weed flora. Increased herbicide use, mechanized tillage, variable water availability, crop establishment by direct seeding rather than transplanting, fertilizer use, mechanized harvesting and seed cleaning, and consolidation of farm units into larger holdings are some factors that cause shifts in weed flora (Haas and Streibig 1982, Liebman and Janke 1990). As these practices become widespread and extensively used, weed flora selected over time are tolerant of the weed control practices employed. Selected weed species are often difficult to control. Increased herbicide use is the most important factor responsible for shifts in weed flora (Haas and Streibig 1982). For example, phenoxy-acid herbicides such as 2,4-dichlorophenoxy acetic acid (2,4-D) have been used extensively in rice and cereals to control broadleaf weeds, resulting in the increase of hard-to-control grass weeds tolerant of 2,4-D.

## Weed control with less labor and less water

Labor for transplanting and hand weeding is becoming more expensive and difficult to find. As a result, farmers have been forced to switch to direct seeding, thus losing the early season advantage of flooding with transplanting to suppress early weed growth, especially of hard-to-control grasses such as barnyardgrass (*Echinochloa crus-galli*).

Rapid industrialization and urbanization compete with agriculture for limited water resources. In addition, much irrigation infrastructure is also poorly maintained, causing water shortages in rice production. Water conservation measures in rice production, such as intermittent flooding and shallow water depths, generally make weed control more difficult. With labor and water shortages and the shift to direct seeding, farmers have few weed control alternatives other than to increase herbicide use.

*Reliance on herbicides.* With less labor and water for weed control, herbicide use in South and Southeast Asia is increasing exponentially. Even with increased herbicide use, crop losses caused by weeds have not declined and may have increased (Heong et al 1995). This effect may be attributable to the continuous use of the same selective herbicides that select for herbicide-tolerant weeds. Few, if any, economical alternatives to herbicides are now available, and this factor exacerbates herbicide dependency.

Increases in herbicide use and dependency will have environmental and sociological costs, such as contamination of surface water and groundwater, adverse effects on nontarget organisms, and risks to human health. In the United States, rice herbicides have been detected in well water. They have polluted agricultural drains and rivers and have caused off-tastes in potable water supplies in California (Cornacchia et al 1984). Similar adverse environmental effects are occurring in South and Southeast Asia as herbicide use increases. We expect that these adverse effects will be even greater as rice production systems become more intensive, given the close proximity of rice fields to the water supply within the entire community.

Herbicide use can be reduced when combined with good husbandry. Recommended herbicide rates are set to ensure that the product will perform over a wide range of environmental conditions, and control the more difficult species. Many farmers in South and Southeast Asia are already applying herbicides at less than recommended rates and achieving satisfactory control. Water, land preparation, seeding, and weed control are closely interrelated in rice production. Good land preparation reduces weed infestations and permits more efficient water use (Heong et al 1995). During 1990-93, in the Muda area in Malaysia, herbicide use declined as a result of an extension campaign on integrated weed management (Ho 1994). Farmers who applied proper land leveling and water management needed to apply herbicide only once, whereas farmers using poor cultural practices had to apply herbicides three or four times to control weeds.

*Resistance to herbicides.* Reliance on herbicides for weed control brings biological repercussions, such as selection and enrichment of genes that confer herbicide resistance in weed populations. Resistant biotypes are common, normally have vigor, and are difficult to control with other herbicides. Some weed populations are accumulating resistance mechanisms and have resistance to many herbicide groups. Resistance to at least 15 classes of herbicides by more than 100 weed species worldwide has been reported, and the area infested with herbicide-resistant weeds is increasing (Jasieniuk et al 1996). Propanil has been used in the United States since 1960 for grass control in rice. The continuous use of propanil on 70% of the rice area in Arkansas has led to the development of resistant populations of *E. crus-galli* (Carey et al 1992). Of equal or greater concern is the rapid appearance of resistance to newer generation herbicides, including the sulfonylureas. Resistant populations of four weeds—*Sagittaria montevidensis, Cyperus difformis, Scirpus mucronatus,* and *Ammannia auriculata*—have developed in California after only 5 yr of bensulfuron field use and resistant populations have been found at 72 sites throughout rice-growing areas in California (Pappas-Fader et al 1994).

*Transgenic herbicide-resistant rice.* Major research efforts are being directed toward developing herbicide-resistant field crops (Dekker and Duke 1995). The primary focus of this research is to incorporate genes conferring resistance to broad-spectrum herbicides such as glyphosate and glufosinate. Both herbicides are environmentally relatively benign. Transgenic herbicide-resistant rice cultivars, including glufosinate-resistant (Datta et al 1992) and sulfonylurea-resistant (Li et al 1992) ones, have already been developed. Transgenic glufosinate-resistant rice has been field-tested in Louisiana with no substantial negative agronomic or quality differences between the transformed and original parent material (Braverman and Linscombe 1994). The cited reason for the keen interest in developing glufosinate-resistant rice is to control "red rice."

Weedy rice and red rice are undesirable early shattering off-types that are morphologically very similar to, and naturally cross with, cultivated rice. Their ability to hybridize with cultivated rice is a major concern if herbicide-resistant rice cultivars are to be released widely. Kerlan et al (1992) reported that the risk of gene dispersal from outcrossing of transgenic glufosinate-resistant rapeseed with weedy *Brassica* spp. was limited. Mikkelsen et al (1996), however, recently demonstrated that transgenic rapeseed could cross with weedy relatives, producing transgenic weed-like plants after only two generations of hybridization and backcrossing. These findings with rapeseed suggest that herbicide-resistant rice and weedy rice have the potential to hybridize and confer herbicide resistance to "weedy" rice. This would have major adverse effects if herbicide-resistant "weedy" rice flourished. The potential for and consequences of such a transfer of herbicide resistance need to be thoroughly considered before transgenic herbicide-resistant rice is released.

### Reduction in herbicide dependency and alternatives

Herbicides alone cannot be relied upon to solve all weed problems in rice. More tools are needed besides good husbandry and a judicious use of minimal amounts of herbicides. Improvement of rice germplasm to enhance weed-suppressing capacity can help in minimizing herbicide use. IRRI has several novel research programs under way to develop allelopathy in rice and to achieve biological control of weeds using indigenous fungi.

Competitive cultivars suppress weeds through the efficient capture of available nutrients, light, and water, whereas allelopathic cultivars have been identified to suppress weeds through the release of chemicals into the environment. Traditionally, competition has been thought of as the most important factor in plant interference. But recent research has shown that there is a good potential to use allelopathy in rice to reduce weed growth significantly in the field (Olofsdotter and Navarez 1996).

Allelopathy is the release by a plant of chemical compounds that affect the growth and development of other living plants. Dilday et al (1991), in observing 10,000 rice accessions in nonreplicated seed increase plots, reported that 3.5% showed allelopathic potential against ducksalad (*Heteranthera limosa*). One allelopathic accession was also able to control 72–95% of a mixed population of *Ammannia coccinea* and *Bacopa rotundifolia* (Lin et al 1992). Because it is difficult to separate the effects of competition and allelopathy in the field, laboratory experiments have been used to eliminate competition as a cause of observed crop-weed interference (Olofsdotter and Navarez 1995). At IRRI, laboratory screening and field experiments showed that 19 of 111 rice cultivars tested suppressed the growth (dry matter) of *E. crus-galli* by >40% in the dry and wet seasons of 1995. Eight of these cultivars reduced weeds by >50% in both growing seasons. Suppression in the field was comparable to root reduction observed in laboratory screening, suggesting that allelopathy was the major part of the interference found (Navarez and Olofsdotter 1996, Olofsdotter and Navarez 1996).

The rice accessions that showed allelopathic activity have different origins and are in different stages of improvement. Characterization of the chemical(s) involved, physiological cost of the mechanism, ecotoxicology, and incorporation of allelopathic potential into a breeding program are some of the challenges to be met. Although many questions remain unanswered, new knowledge on allelopathic and competitive abilities is likely to result in a wider use of weed-suppressing rice cultivars.

Pathogenic fungi that occur naturally on weeds also offer an environmentally sound aid to control weeds in rice (Watson 1994). Biological weed control research began in 1991 at IRRI and focuses on the following major weeds of rice: *Echinochloa crus-galli* and *E, colona, Eleusine indica, Fimbristylis miliacea, Cyperus rotundus, C. iria,* and *C. difformis, Mimosa invisa, Monochoria vaginalis,* and *Sphenoclea zeylanica.*

This research focuses on the discovery and propagation of indigenous fungal pathogens from weed hosts for weed control. Disease and mortality of target weeds are promoted by augmenting natural pathogen populations through the inundatory application of high levels of spore suspensions. Virulent indigenous pathogens with biocontrol potential have been isolated from all of the targeted species except *M. vaginalis.* Optimum conditions for disease expression and damage to the weed have been determined under regulated environmental conditions for most of the weed-pathogen systems under study.

A spore suspension of an *Alternaria* species was used to effectively control *Sphenoclea zeylanica* in a farmer's field in Central Luzon (Mabbayad and Watson 1995). The control provided by a standard herbicide treatment of 2,4-D was inferior. This trial was repeated thrice in Laguna and once in Leyte with the collaboration of staff from the Visayas State College of Agriculture. Similar results were found. *S. zeylanica* is the only plant species susceptible to the *Alternaria* isolate.

Six pathogenic fungi have been isolated from *Echinochloa* species. Of these, two were virulent on three *Echinochloa* species (nonpathogenic to rice) and needed a relatively low dew period duration compared with other fungi tested (Zhang et al 1996). Three of the *Echinochloa* pathogens produce chemicals that are active on the three *Echinochloa* species tested. Three of the chemicals are known phytotoxins, whereas the fourth appears to be a novel compound. Initial field trials with the fungus *Exserohilum monoceras* provided 50–80% control of *Echinochloa* species. Two additional *Echinochloa* pathogens have provided similar levels of control in the field. Leaf wetness duration is a critical factor and can limit the performance of these fungi for weed control in tropical areas where evaporation is high. An oil emulsion has overcome this limitation, but it was slightly phytotoxic to rice. In pot experiments, a dry-powder formulation that floated on the water surface effectively delivered the inoculum to the target weeds with no damage to rice.

In studies on other weeds, a virulent pathogen from *Eleusine indica* has been evaluated for biocontrol potential. Three *Curvularia* spp. have been isolated from *Cyperus* spp. and *Fimbristylis miliacea* that demonstrate different degrees of virulence on these sedges. *Mimosa invisa* was controlled in the field by applying a spore suspension of a fungal pathogen without any damage to mungbean, but this isolate damaged some upland rice cultivars.

Challenges to be met in the biocontrol program are optimization of propagule production and infection in the field, technology transfer, and integration within weed management systems at the farm level. As these challenges are met, fungal pathogens will become more attractive and more widely used in integrated weed management.

## References

Altieri MA. 1987. Agroecology: the scientific basis of alternative agriculture. Boulder, Colo. (USA): Westview Press. p 173-185.

Braverman MP, Linscombe SD. 1994. Field evaluation of genetically engineered glufosinate-resistant rice lines. Baton Rouge, La. (USA): Agricultural Experiment Station, Louisiana State University. 37(3):29.

Carey VF III, Talbert RE, Baltazar AM, Smith RJ Jr. 1992. Evaluation of propanil-resistant barnyardgrass in Arkansas. Proceedings of the Rice Technical Working Group, 1992. Little Rock, Ark. (USA): Rice Technical Working Group. 24:120.

Cornacchia JW, Cohen DB, Bowes GW, Schnage RJ, Montoya BL. 1984. Rice herbicides: molinate and thiobencarb. CSWRCB special project report. Sacramento, Calif. (USA): State Water Resources Control Board. 84-4sp.

Datta SK, Datta DK, Soltanifar N, Donn G, Potrykus I. 1992. Herbicide resistant *Indica* rice plants from IRRI breeding line IR72 after PEG-mediated transformation of protoplasts. Plant Mol. Biol. 20:619-629.

Dekker J, Duke SO. 1995. Herbicide-resistant field crops. Adv. Agron. 54:69-116.

Dilday RH, Nastasi P, Lin J, Smith RJ Jr. 1991. Allelopathic activity in rice (*Oryza sativa* L.) against ducksalad (*Heteranthera limosa* (Sw.) (Willd.). In: Proceedings of a Symposium on Sustainable Agriculture for the Great Plains. Washington, D.C. (USA): United States Department of Agriculture. p 193-201.

Haas H, Streibig JC. 1982. Changing patterns of weed distribution as a result of herbicide use and other agronomic factors. In: LeBaron HM, Gressel J, editors. Herbicide resistance in plants. New York John Wiley & Sons. p 57-79.

Heong KL, Teng PS, Moody K. 1995. Managing rice pests with less chemicals. GeoJournal 35(3):337-349.

Hill JE, Smith RJ Jr, Bayer DE. 1994. Rice weed control: current technology and emerging issues in temperate rice. Austr. J. Exp. Agric. 34:1021-1029.

Ho NK. 1994. Integrated weed management of rice in Malaysia: some aspects of the Muda irrigation scheme's approach and experience. In: Sastroutomo SS, Auld BA, editors. Appropriate weed control in Southeast Asia. Proceedings of an FAO-CAB International workshop, Kuala Lumpur, Malaysia, 17-18 May 1994. Wallingford (UK): CAB International. p 83-97.

Jasieniuk M, Brûlé-Babel AL, Morrison IN. 1996. The evolution and genetics of herbicide resistance in weeds. Weed Sci. 44:176-193.

Kerlan MC, Chevre AM, Eber F, Baranger A, Renard M. 1992. Risk of assessment of outcrossing of transgenic crop seed to related species. I. Interspecific hybrid production under optimal conditions with emphasis on pollination and fertilization. Euphytica 62:145-153.

Kon KF. 1993. Weed management: towards tomorrow (with emphasis on the Asia-Pacific Region). Proceedings of the 14th Asia-Pacific Weed Science Society Conference. Brisbane: Asia Pacific Weed Society. p 1-9.

Kropff MJ, Moody KM. 1992. Weed impact on rice and other tropical crops. In: Combellack JH, Levick KJ, Parsons J, Richardson RB, editors. Proceedings of the First International Weed Control Congress. Melbourne: Weed Science Society of Victoria Inc. p 123-126.

Li Z, Hayashimoto A, Murai N. 1992. A sulfonylurea herbicide resistance gene from *Arabidopsis thaliana* as a new selectable marker for production of fertile transgenic rice plants. Plant Physiol. 100:662-668.

Liebman M, Janke RR. 1990. Sustainable weed management practices. In: Francies CA, Flora CB, King LD, editors. Sustainable agriculture in temperate zones. New York: John Wiley & Sons. p 111-143.

Lin J, Smith RJ Jr, Dilday RJ. 1992. Allelopathic activity of rice germplasm on weeds. Proceedings of the Southern Weed Science Society. 45:99.

Mabbayad MO, Watson AK. 1995. Biological control of gooseweed (*Sphenoclea zeylanica* Gaertn.) with an *Alternaria* sp. Crop Prot. 14:429-433.

Mikkelsen TR, Andersen B, Jørgensen RB. 1996. The risk of crop transgene spread. Nature 380:31.

Navarez D, Olofsdotter M. 1996. Relay seeding technique for screening allelopathic rice (*Oryza sativa*). In: Brown H, Cussans GW, Devine, MD, Duke, SO, Fernandez-Quintanilla C, Helweg A, Labrada RE, Landes M, Kudsk P, Streibig JC, editors. Proceedings of the Second International Weed Control Congress. Slagelse (Denmark): Department of Weed Control and Pesticide Ecology. Vol. 4. p 1285-1290.

Olofsdotter M, Navarez D. 1996. Allelopathic rice for *Echinochloa crus-galli* control. In: Brown H, Cussans GW, Devine MD, Duke SO, Fernandez-Quintanilla C, Helweg A, Labrada RE, Landes M, Kudsk P, Streibig JC, editors. Proceedings of the Second International Weed Control Congress. Slagelse (Denmark): Department of Weed Control and Pesticide Ecology. Vol. 4. p 1175-1181.

Olofsdotter M, Navarez D. 1995. Approaches in rice allelopathy research. In: Proceedings of the 15th Asian-Pacific Weed Science Society Conference. Vol 1A. Tsukuba (Japan): Weed Science Society of Japan. p 315-321.

Pappas-Fader T, Turner RG, Cook JF, Butler TD, Lana PJ, Caniere M. 1994. Resistance monitoring programs for aquatic weeds to sulfonylurea herbicides in California rice fields. In: Proceedings of the Rice Technical Working Group, 1994. New Orleans, La. (USA): Rice Technical Working Group. 25:165.

Watson AK. 1992. Biological and other alternative control measures. In: Combellack JH, Levick KJ, Parsons J, Richardson RB, editors. Proceedings of the 1st International Weed Control Congress. Vol I. Melbourne: Weed Science Society of Victoria Inc. p 64-73.

Watson AK. 1994. Biological weed control and prospects for bioherbicides development in the Philippines. Phillip. J. Weed Sci. Special Issue 64-81.

Zhang WM, Moody K, Watson AK. 1996. Responses of *Echinochloa* species and rice (*Oryza sativa*) to indigenous pathogenic fungi. Plant Dis. 80:1053-1058.

## Notes

*Authors' addresses:* M. Olofsdotter, International Rice Research Institute (IRRI), P.O. Box 933, 1099 Manila, Philippines, and the Royal Veterinary and Agricultural University, Frederiksberg, Denmark; A. Watson, IRRI and McGill University, Quebec, Canada; C. Piggin, IRRI. m.olofsdotter@cgnet.com and mol@kvl.dk a.watson@cgnet.com and watsona@agradm.lan.mcgill.ca c.piggin@cgnet.com

*Citation:* Dowling NG, Greenfield SM, Fischer KS, editors. 1998. Sustainability of rice in the global food system. Davis, Calif. (USA): Pacific Basin Study Center, and Manila (Philippines): International Rice Research Institute.

CHAPTER 11

# Management of water as a scarce resource: issues and options in rice culture

S.I. Bhuiyan, T.P. Tuong, and L.J. Wade

Rice culture is known for its crucial dependence on an adequate supply of water. But how much water is really needed for producing the crop? How can water management and rice production systems be improved to obtain more rice per unit of water supplied? How can the agrochemicals associated with rice production be managed for minimal impact on the quality of water resources that are vital for sustainable agriculture? These and other related questions must be adequately addressed to achieve the needed rice production growth in Asia, where water for agriculture is becoming increasingly scarce. This paper addresses these issues in a holistic perspective that elucidates options from the farm to the irrigation system and basin level. Prospective technological innovations in areas such as crop management and varietal development, which should improve water use efficiency in rice culture, are also discussed.

## Importance of water in rice culture: present and future

As an aquatic plant, rice grows better and produces higher grain yields when grown in a flooded soil than when grown in dry soil. Besides supplying water to meet the plant's evapotranspiration demand, the ponded water layer also helps suppress weed growth and increase the availability of many nutrients (De Datta 1981). Unlike other food crops, rice suffers from water stress even at soil water contents that exceed field capacity. Thus, a reliable and adequate water supply is crucial for high yield performance of rice. Because rice culture evolved in response to the amount and reliability of water supply, distinct ecosystems for rice have evolved. They have been characterized as upland, rainfed lowland, irrigated, and flood-prone, defined by their agrohydrology (IRRI 1989).

In modern rice culture, the degree of control over water determines the level of production technologies employed by rice farmers. In rainfed ecosystems, variability in the amount and distribution of rainfall is the most important factor affecting crop growth and yield. The planting season begins with the onset of the monsoon rain. In-season drought is common, however, and limits the yield potential of rice. In addition, alternate wet-and-dry field conditions cause nitrogen (N) loss and high weed infestation. Farmers in most rainfed ecosystems therefore use the less risky traditional varieties and small amounts of fertilizers. Except in favorable rainfed areas with shallow water depths, modern rice technologies have contributed little to improved rainfed rice yields, mainly because of a lack of water control.

Irrigation has contributed significantly to the success of the Green Revolution in Asia. In the past three decades, the growth in rice yield in the irrigated ecosystem has been 2.6% per year (Hossain 1995). Only about 55% of rice land is irrigated, but it produces 76% of worldwide production (IRRI 1993). By 2025, the Asian population is expected to increase by 53% and the demand for rice by 69% (Hossain 1995). Although more recent estimates expected lower future demand for rice (about a 40% increase, M. Agcaoili-Sombilla, personal communication, 1997), the increase is still substantial. Irrigated rice lands will have to satisfy a large proportion of this additional demand and at the same time allow the development of other crops. We will also need appropriate technologies for rainfed systems to meet the growing demand for rice. This paper examines the current supply and quality of water for rice culture, and opportunities for increasing water use efficiency while improving or sustaining water quality over the coming decades.

## Water—a scarce and declining resource

### Present scarcity and future scenarios

Fresh water is a finite resource. Only 38 million km$^3$ of water, or 2.7% of all the water on Earth, is fresh or nonsaline and suitable for consumption by terrestrial plant and animal life (Sarma 1986). About 76% of this amount is held in permanent ice caps and glaciers, and 11% is held in formations at depths greater than 1 km. Only about 4.5 million km$^3$ of fresh water is available for consumption, of which 97% is present as underground water within 1 km depth. Only 0.14 million km$^3$ of water is present in lakes, rivers, and the atmosphere.

Large-scale irrigation development has slowed considerably since the early 1980s, because engineering and environmental costs of exploiting new but feasible sources of water are increasing. Although the total water use in Asia, about 85% of which is used in agriculture, has increased by nearly 3% annually from 1950 to 1990, per capita water availability has declined by 40–60% over the same period (Gleick 1993). India, Pakistan, the Philippines, and Vietnam are expected to suffer sharp declines in per capita water availability over the next two decades (Fig. 1; IRRI 1998).

The urban population in Asia is expected to increase from about 35% of the total population in 1990 to more than 50% in 2025 (IRRI 1998). If demand outpaces supply of water resources, intersectoral competition will intensify, with adverse effects on agricultural water availability and food production, as well as on environmental quality. In the Angat multipurpose project in Luzon, Philippines, for example, the amount of water diverted for Metropolitan Manila increased consistently at about 10% per annum during 1980-95, with a corresponding decrease in the supply for irrigation to its 28,000-ha rice fields. A similar diversion of irrigation water to the urban sector is occurring in the Jatiluhur irrigation project of West Java, Indonesia, and in the Guangxi Autonomy Region of China. Because urban and industrial demands are likely to receive priority over irrigation, agricultural productivity would

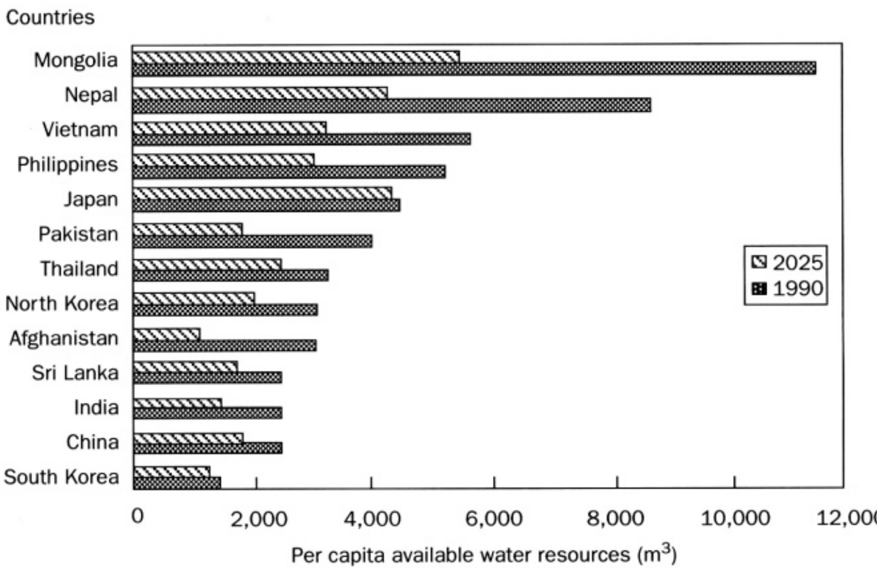



**Fig. 1.** Per capita available water resources in selected Asian countries (after Gleick 1993).

be reduced in such irrigation systems, especially in years with low water supply at their sources.

## Gap between water "need" and "use" in rice culture

The use of water in traditional rice culture is highly inefficient. For each kg of irrigated rice, about 5,000 L of water are diverted at the source of the canal system (IRRI 1995). The actual field-level need is only about 25–30% of that amount. The gap between the "need" and the "use" of water in rice culture can be understood clearly by looking into the two major water-consuming components in transplanted rice culture: land preparation and crop irrigation.

*Land preparation.* Preparing land for crop establishment normally involves supplying enough water to saturate the soil (land soaking) and maintain a water layer for plowing, harrowing, puddling, and leveling before rice seedlings are transplanted. The amount of water required for land preparation is about 150–250 mm, depending on the initial soil water condition and soil type. But the actual amount used for this purpose may be as high as 1,500 mm (Ghani et al 1989). Rice is grown mostly in clayey soils and land soaking for the wet-season rice crop generally starts following the long dry period when the soil is cracked. In fields with permeable subsoil, up to 60% of the water applied for land soaking may move down the cracks, bypassing the topsoil matrix (Tuong et al 1994, Tuong and Cabangon 1996). Most of this water is lost from the field through lateral drainage. Cracks in clayey soils may not close even after prolonged wetting; therefore, bypass flow through cracks may continue until the field is puddled.

Another reason for excessive water use during land preparation is the long period over which farmers continue land soaking and tillage activities. In the transplanted rice system, farmers keep the main field flooded during the 1-month period when seedlings are grown in small seedbeds until ready for transplanting. If the canal that serves a block of farms has slow-flowing water, 2 months or more are taken before all farmers in the canal service area can complete land preparation (Valera 1977). Most of the water applied to the field during this period is lost by runoff, seepage, percolation, and evaporation.

*Crop irrigation.* Irrigation water supplied to the cropped field is used by evapotranspiration from the rice field, deep percolation, seepage, and overland runoff (Fig. 2). Excessive percolation loss can occur even in puddled fields through some nonpuddled spots that are unintentionally omitted during land preparation and through the under-bund areas that remain porous. Tuong et al (1994) found that a 1% nonpuddled area can increase the percolation water loss by a factor of 5. Under-bund percolation caused a further 2- to 5-fold increase in water loss by percolation, depending on the size of the field.

Farmers prefer to maintain a relatively high water depth to control weeds and reduce the frequency of irrigation (and hence labor cost), and to store water as insurance against possible shortage, but percolation loss increases as the depth of water standing in the field increases (Tabbal et al 1992, Tuong et al 1994). Water loss from target areas by seepage and surface overflow also increases with greater water depths.

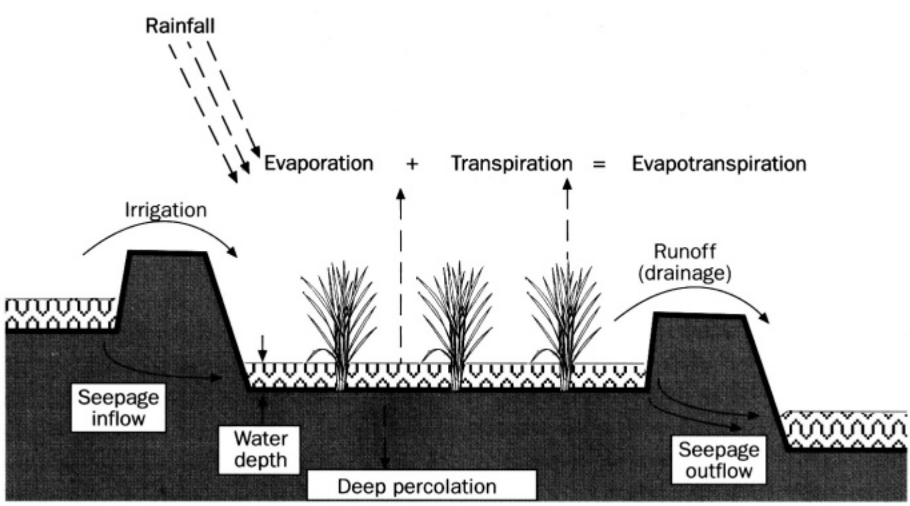



**Fig. 2.** Components of water balance in a rice field.

## Water quality deterioration—causes and consequences

*Soil erosion.* Soil erosion in upper watershed areas and consequent sedimentation downstream are constantly undermining the quality of irrigation water in reservoir-backed, canal-supplied rice production systems. Inappropriate land use and deforestation in the upper watershed areas aggravate the erosion-sedimentation problem. At the reservoir level, excessive sedimentation will fill up the reservoir's active storage space, resulting in a reduction of the project's service capacity and useful life. A survey of eight reservoirs in India established that the sedimentation rates in seven of them were 2.9 to 16.5 times higher than expected (Dogra 1986). Below the reservoir, canals silt up quickly when the sediment load is high. The cost of desilting canals to maintain their flow capacity is high.

*Irrigation-induced waterlogging.* Waterlogging and salinization of the soil are the most pervasive damages caused by badly designed or poorly managed irrigation systems. Irrigation-induced waterlogging is a major problem in tropical Asia, but its actual extent is not well established. Estimates suggest that about 6 million ha of irrigated land are waterlogged in India. About 22% of the irrigation systems surveyed in the Philippines have 5% or more of their areas waterlogged. A high rate of water loss by seepage and percolation from rice fields and unlined canals may raise the underlying water table, thus affecting low-lying areas first. Heavy rainfall in the wet season may cause large-scale inundation, with severely affected areas becoming unproductive.

*Salinization.* Irrigated areas are basically large evaporation pans where distilled water is returned to the atmosphere in the vapor phase, and salts remain behind in the soil. Therefore, salinity buildup is often associated with irrigated agriculture. In the humid tropics, salinity normally does not build up because of strong leaching of the soil by high rainfall in the monsoon season. In the semiarid tropics, however, rainfall is low, and salinization is aggravated when salty groundwater rises from continued percolation and seepage from irrigated fields and leaky irrigation canals. When the water table rises to within about 2 m from the soil surface, salts are brought up to the crop root zone by soil capillarity (Khosla et al 1980). Salinization reduces crop yields and may eventually cause complete crop failure, forcing farmers to abandon the land. Postel (1989) estimated that 36% of irrigated land in India, 15% in China, and 20% in Pakistan has been damaged by irrigation-induced salinization.

*Contamination by leachate from reclaimed acid sulfate soils.* Reclamation of acid sulfate soils, which cover significant areas in Thailand, Vietnam, and Indonesia, involves leaching of acidic toxicity from the crop root zone. The process contaminates surface water, which may affect crops and soils in surrounding areas (Dent 1992, Minh et al 1997a). Acidic toxicities, especially aluminum, are particularly hazardous to fish and aquatic organisms whose threshold concentrations are far less than those for plant roots (van Breemen 1993). In Indonesia, Klepper et al (1990) reported a 10-fold reduction of fish yield in areas reclaimed from acid sulfate soils.

*Nitrate-nitrogen contamination.* Increased use of N fertilizer may result in a higher $NO_3$ content in groundwater commonly used for domestic water consumption. High concentrations of nitrate-nitrogen ($NO_3$-N) in drinking water, usually those in excess of 10 ppm, are considered unsafe for human consumption (Viets and Hagemen 1976), as they may cause methemoglobinemia (blue-baby syndrome) and carcinogenic effects (Follet and Walker 1989).

In a study of two large irrigation systems in Luzon, Philippines, where farmers have been growing two rice crops per year using moderate levels of N fertilizers for several decades, $NO_3$-N concentrations found in groundwater were very low (Castañeda and Bhuiyan 1991). In contrast, a study conducted at Batac, Ilocos Norte, Philippines, has shown high $NO_3$-N concentrations in groundwater. At the Batac site, the combination of very intensive land use (two or three crops per year, with one rice crop in the wet season), relatively light-textured soil (loam), application of heavy doses of N in the dry season to upland crops grown after wet-season rice (average rate applied was 348 kg N $ha^{-1}$), frequent irrigation, and the rise of groundwater to shallow depths in the wet season has resulted in a dry-season average groundwater $NO_3$-N concentration of 9.7 ppm (Gumtang et al 1998). Some groundwater samples exceeded the average by 3–4 times, making the water extremely hazardous for consumption. More research is needed on the process of nitrate pollution of groundwater from rice fields.

*Pesticide contamination.* Pesticides in fresh surface water may enter the food chain. Although acute toxicities have a lethal effect on the fish population (Lim and Ong 1977), sublethal and chronic exposures to pesticides are more insidious and difficult to identify. Sublethal exposure to pesticides may suppress reproduction and result in pesticide-resistant strains of fish (Cheng 1990).

In a recent case study in two irrigated rice areas in Luzon, Philippines, where nearly all farmers used pesticides, many of the pesticides reached the shallow groundwater aquifers beneath irrigated rice fields. Endosulfan was found in about 80% of the samples, monocrotophos in 54%, butachlor in 24%, methyl parathion in 24%, chloropyrifos in 7%, and carbofuran in 6% of the samples (Castañeda and Bhuiyan 1996). Endosulfan and butachlor are considered moderately hazardous and the rest extremely hazardous to human health. Their concentrations are still far below the daily acceptable intakes based on toxicological standards (FAO/WHO 1977). With the increasing cost of labor and consequent shift to direct seeding of rice, however, herbicide use has increased, especially in the Philippines, Thailand, and Malaysia. The levels of many groundwater pesticides, other than the six cited above, are not clear. Few data are available on herbicide concentration in groundwater. Nor is their persistence behavior in groundwater understood. Therefore, we need to study the contamination potential of new and untested insecticides and herbicides, and to develop appropriate policies to safeguard water quality.

## Opportunities for increasing irrigation efficiency in rice

### Farm-level opportunities

*Land preparation phase.* Water loss in land preparation through bypass flow can be curtailed by eliminating or reducing soil crack formation and water flow into cracks. Shallow dry-tillage of the soil soon after harvesting the previous crop allows the topsoil to act as mulch, thus reducing soil dehydration and its consequent cracking. Also, small soil aggregates formed by the tillage block the cracks and reduce water flow. Tuong and Cabangon (1996) found that in the clay soil of the IRRI experimental farm, shallow dry-tillage could save about 200 mm of water in land preparation. Because of increased access to high-powered tractors in rural areas, dry-tillage will become more feasible for farmers. This technique is practiced extensively in the Muda irrigation project of Malaysia and is credited with water savings and timely rice crop establishment benefits in the project area (Ho et al 1993).

Shortening land preparation time reduces water loss in the irrigation system (Wickham and Sen 1978). Most rice irrigation systems allow water to be available to farmers for much longer periods than necessary to complete all irrigation activities. Consequently, farmers' land use schedules and water use remain inefficient. Tailoring water delivery periods to the near optimal duration for land preparation and crop growth will reduce water wastage. To be successful with such actions, users must have confidence in the reliability of water delivery and the benefits of strict scheduling.

*Crop growth phase.* When a rice field of medium soil type was maintained at a nearly saturated soil condition and weeds were controlled by herbicides, about 45% less water was consumed, without any yield loss, than when the standard continuous shallow (5–2 cm deep) submergence was maintained (Tabbal et al 1992). The difference was attributable mostly to reduced percolation loss because of the absence of standing water in the field. If the weed pressure is high, however, shallow flooding can be maintained from the beginning up to the panicle initiation stage when the field is fully shaded by the crop, and then the continuous saturated soil regime can be established for the remaining period. This practice will save significant amounts of water without reducing yield, but it requires additional labor and supervision. For farmers using a canal irrigation system to adopt such measures, reliable water deliveries must be maintained, an uncommon feature in Asian rice-producing countries. Plastic sheet lining of the bund faces, or sealing the faces with sticky mud at the beginning of the season, can reduce lateral movement of water into the bund, and hence reduce under-bund percolation loss. Development of unpuddled spots can be eliminated by good land leveling and by careful puddling activity.

Recent breeding work has continuously reduced the duration of the rice growth period. Such a reduction results in less water demand and has contributed greatly to increasing water use efficiency, especially with yield improvement of new varieties.

*Opportunities with wet-seeded rice culture.* Availability of early maturing rice varieties and effective herbicides, increasing cost of labor, and declining profitability of rice production have encouraged rice farmers in some countries to switch from transplanted to direct-seeded rice systems. Direct seeding comes in two forms: wet seeding and dry seeding.

In wet-seeded rice (WSR), pregerminated seeds are broadcast onto the puddled soil. After the crop is established, WSR is maintained in much the same manner as transplanted rice (TPR). Changing from a transplanted to a wet-seeded rice system automatically advances the farmers' crop establishment schedule, with a shorter period taken to prepare the land, as seeds require only 24–36 h of soaking and incubation before they are ready for wet seeding. In contrast, in the transplanting period, seedlings are nurtured in the seedbed for 1 month, and farmers have no reason to complete land preparation before the seedlings are ready for transplanting (Bhuiyan et al 1995). The WSR system required 27% less water to complete land preparation than the TPR (Table 1). Because farms were better leveled for facilitating germination, WSR farmers were able to maintain less water depth during crop growth, and the crop had better lodging resistance. Furthermore, WSR gives higher yield than TPR when water stress occurs (Table 2) (Bhuiyan et al 1995). Where WSR is properly introduced, farmers on their own are adopting land and water management practices that lead to better water use efficiency (Bhuiyan et al 1995). Promoting this development involves little cost or risk of failure. In certain areas where the WSR system has been introduced, its popularity has spread very quickly. More studies are needed to determine why WSR adoption is still limited, and how it can be spread more widely.

*Further opportunities with dry-seeded rice culture.* Dry-seeded rice (DSR) technology offers further opportunity for significant water savings in irrigation systems by making more efficient use of rainfall for land preparation and crop establishment. In DSR, nonpregerminated seeds are sown onto dry-plowed soil that is dry or moist,

**Table 1. Water use, water use period for land soaking and land preparation, and water depth maintained in the field in wet-seeded rice (WSR) and transplanted rice (TPR) in Maligaya, Philippines, 1990-91 dry season.**

| | WSR[a] | TPR[b] |
|---|---|---|
| Water use (mm) | | |
| Land preparation | 740 | 890 |
| Crop irrigation | 1,010 | 1,300 |
| Total | 1,750 | 2,190 |
| Time taken to complete land preparation (d) | 6 | 24 |
| Water depth (cm) at | | |
| Crop establishment | 1 | 3 |
| Crop growth | 6 | 7 |
| Yield (t $ha^{-1}$) | 7 | 6.5 |

[a] Turnout service area = 68 ha. [b] Turnout service area = 35 ha.
Source: Bhuiyan et al 1995.

**Table 2. Yields of wet-seeded rice (WSR) and transplanted rice (TPR) under different water regimes, Maligaya, Philippines, 1990-91 dry season.**

| Water regime[a] | Yield (t ha$^{-1}$) | | |
|---|---|---|---|
| | WSR | TPR | Difference[b] |
| W1 | 7.6 | 7.4 | 0.2$^{ns}$ |
| W2 | 7.3 | 6.7 | 0.6** |
| W3 | 7.0 | 6.3 | 0.7** |
| W4 | 6.1 | 5.3 | 0.8** |
| W5 | 6.4 | 6.0 | 0.4* |
| W6 | 5.2 | 4.2 | 1.0** |

[a] W1 = fully irrigated, 5–7 cm depth (no stress), W2 = saturated soil throughout growing season, W3 = mild vegetative stress (10 d without watering starting at 30 DAS or 9 DAT), W4 = severe vegetative stress (same as W3, but stress continued for 20 d), W5 = mild reproductive stress (10 d without watering starting 50 DAS or 29 DAT), W6 = severe reproductive stress (same as W5 but stress continued for 20 d). [b]ns = not significant, ** = significant at 1%, * = significant at 5%.
Source: Bhuiyan et al 1995.

but unpuddled. In contrast to TPR, which consumes a large amount of irrigation water in preparing the land for crop establishment, DSR is first established and nurtured by (premonsoon) rainwater as a nonirrigated crop. Later in the season, when the canal water supply has been started, rice may be fully irrigated. Data from Malaysia's Muda irrigation scheme indicate that this practice could save up to 500 mm of irrigation water (Ho Nai Kin et al 1993). In 1991, when irrigation water could not be released because of very low reservoir storage, farmers grew DSR that yielded an average of 3.9 t ha$^{-1}$. In a similar situation in 1978, these farmers could not grow any rice because TPR was their only choice and it could not be established for lack of water. Adoption of DSR allows the irrigation system to achieve better rainfall use and reservoir water conservation.

## Irrigation system-level opportunities

The irrigation system is more than the sum total of the farms and canals when it comes to the issue of efficiency of water use. Critical determinants of system efficiency are the capacity to control and deliver water in a timely manner, the use of delivered water, communication with water users, quality of feedback, and commitment to cooperation.

A recent study of 15 irrigation systems in South and Southeast Asia indicated little systematic measurement of performance by system managers. Wide gaps existed between operational targets and actual achievements, little feedback came from the field, and farmers could not respond to information if it was available. Governments were spending less and less money on system operation and maintenance. Only a few cases showed evidence of concern for maintaining the physical resource base necessary for productive agriculture. The study concluded that improving managerial capacity should be the first step toward performance improvement of these systems

(Murray-Rust and Snellen 1993). Few systematic efforts have been made to remedy defects at the systems level.

Recent years have seen a global recognition of the value of consulting and involving water users in water management plans. As the value of water is better internalized by users and is priced realistically, a system of joint responsibility should result in better water use efficiency.

A recent review of 208 World Bank-funded irrigation projects around the world showed that Asian rice irrigation systems were unique in that their water efficiency problems stem from incompatibility between design concept and operational objectives. Their design is aimed at slow, continuous water delivery, whereas they are expected to be operated as reticulated systems with capacity to deliver water on demand (World Bank 1994). The problem is exacerbated by the opposing climatological conditions of excess water during the monsoon months—when rice is essentially the only crop grown—and water scarcity during the dry season—when many different crops, including rice, are grown. Most irrigation systems have problems in handling the wet-dry-wet transitions, leading to major sacrifices in water efficiency.

Large rice irrigation systems in the humid tropics are mostly designed and operated for continuous flow of canal water regardless of the amount of rainfall occurring in their command area. Nonuse of rainfall and complete dependence on canal supply in the early part of the wet season lead not only to wasted water but also to delayed planting. Adoption of DSR or WSR systems should allow a more efficient use of rainfall and facilitate more intensive cropping. Better use of rainfall in the field enables conservation of water in the reservoir to increase the service area of dry-season irrigation, when water scarcity is acute. Improved use of rainfall will also reduce waterlogging problems in lower areas of the system. In large pump-supported irrigation systems, better use of rainfall can be translated directly into economic benefits derived from reduced pumping cost.

### Basin- or watershed-level opportunities

The watershed or water basin is the third and final geographic focus in this analysis of water efficiency issues and options in rice culture (the other two being the farm and the irrigation system). Because basin water has multiple uses, off-site effects of increasing water efficiency at the farm or irrigation system level must be carefully assessed. Because water bodies in a basin or watershed are interconnected through the hydrological cycle, water quality must be maintained in lakes, rivers, reservoirs, irrigation and drainage canals, and groundwater. When downstream flow from an irrigation system is the source of water, for example, increased water efficiency upstream may adversely affect the downstream enterprise. Another example is the possible effect of lowering the water table in the groundwater aquifer that supplies water for domestic use, which must depend on pumping from shallow water tables in the same aquifer. Similar issues of water quality should also be considered and properly addressed.

## Opportunities for increasing crop water use efficiency in rainfed rice culture

### Opportunities with crop management technologies

*Timeliness of establishment and crop intensification.* Crop water use efficiency may be increased by improving the timeliness of rice culture relative to the prevailing seasonal conditions. Because up to 700 mm of cumulative rainfall may be needed to complete land preparation for transplanting (Saleh and Bhuiyan 1995, My et al 1995), a significant part of the growing season may be lost by waiting for adequate rains for soil puddling. Late transplanting may reduce productivity because of the consequent reduction in crop duration and yield potential, especially in the traditional, strongly photoperiod-sensitive varieties. Late transplanting may also expose the crop to greater risk from late-season drought.

Direct dry seeding allows earlier establishment of the crop than transplanting or wet seeding, because less water is required for land preparation and crop establishment. Earlier seeding offers the prospect of earlier harvest, especially if shorter-duration, less photoperiod-sensitive varieties are used. Such an earlier harvest may reduce exposure of rice to late-season drought, which is often responsible for the greatest yield loss in rainfed lowlands (Fukai et al 1995). Reduced crop duration, with improved synchronization of sensitive stages with periods of the growing season expected to be more favorable on average, should further improve mean yield and its reliability. Earlier harvest may then permit farmers to grow a short-duration postrice crop on residual moisture (Saleh and Bhuiyan 1995, Pascua et al 1998). Thus, the dry-seeded rice system should make the best use of rainwater and offer the prospect of increased cropping intensity in rainfed conditions.

*Establishment, seedling vigor, and weed control.* The traditional system of transplanting rice on puddled soils offers major benefits for weed control. Dry seeding of rice may expose the crop to a number of risks during crop establishment. A rain break after sowing could result in seed loss. The stand may be thinned or lost to seedling drought, or seedling vigor may be impaired. Weeds may emerge before or with the rice seedlings. Seedlings of dry-seeded rice lack the early size advantage of transplants. Rice's adaptation to anaerobic soil conditions is not helpful until water is ponded and weeds are submerged in the bunded fields as rainfall intensifies later in the season.

Transplanting is therefore a compromise for yield stability—less yield may be lost from weed competition but at the cost of a lower yield potential from delayed sowing, reduced system intensification from any foregone second crop, and lower crop water use efficiency. In contrast, dry seeding may offer the prospect of a higher yield potential with the opportunity for a second crop, as long as a suitable plant stand relatively free from weeds can be established. To fully capitalize on the potential advantages of direct dry seeding for both yield and yield stability, research is needed to develop integrated strategies for reliable establishment of direct dry-seeded crops with adequate management or suppression of weeds. The potential contribution of short-residual, postemergence herbicides should be fully explored.

*Nutrient balance and sustainability.* The traditional system of transplanting rice on puddled soils also offers advantages for nutrient availability, because nutrients are less available in drying soils. A change to dry seeding, with the consequent advance in sowing time, would help capture nitrate formed during the dry-wet transition at the beginning of the growing season, thus reducing N loss to seepage and groundwater (George et al 1994). If the system is intensified with a short-duration legume, some additional benefits may accrue to the N balance, if N loss during the aerobic to anaerobic transition can be minimized (Ladha et al 1996). Given the greater threat from early weed competition in dry seeding, however, proximity of nutrient supply to the roots of the emerging seedling may be important for early vigor, especially for less mobile elements such as phosphorus. Manipulation of controlled-release fertilizer and root system development may be the key to optimizing nutrient release and capture in fluctuating water environments of the rainfed lowlands (Wade et al 1997a). Long-term changes in soil organic matter content and soil nutrient-supplying capacity require further clarification in these contrasting soil conditions (Wade and Ladha 1995).

## Opportunities with crop improvement technologies

Inherent in the performance of dry-seeded rice in water-limited conditions is the need to establish a uniform, vigorous stand of rice capable of competing with weeds. Although crop management is the basis of any effective strategy for establishing a good stand and competing with weeds, selection of improved cultivars may also be helpful. Most cultivars, whether traditional or improved, have been selected for performance in transplanted conditions. Breeding lines are now evaluated under dry-seeding conditions, and selections are made for quality of plant stand and for seedling vigor (Sarkarung et al 1995). A rapid increase in plant height and rapid expansion of leaf area are usually considered advantageous for weed competitiveness. But yield trade-offs by incorporating canopy traits for greater competitiveness are not likely to impede crop performance under water-limited conditions (Bastiaans et al 1997).

In addition to plant characteristics for more effective integrated weed management, rice varieties can also be selected for reduced exposure to drought. Drought resistance can be achieved by three strategies: escape, avoidance, and tolerance (Ludlow and Muchow 1990). Breeders have been most successful in manipulating drought escape, where exposure to drought is minimized by reducing crop duration or minimizing coincidence of sensitive stages with periods of the growing season in which water deficit is likely. The change to direct seeding, together with selection of short-duration, photoperiod-insensitive cultivars, is a drought escape strategy. This strategy also provides some opportunity to partition water use more efficiently by devoting a larger proportion to grain production. Further gains in water use efficiency should be possible by exploiting drought avoidance and drought tolerance. With the former, the plant avoids drought by extracting additional reserves of soil water, such as by having a superior root system. With the latter, the plant tolerates some desiccation by physicochemical changes, such as osmotic adjustment.

Much effort is currently being directed to developing molecular markers for a greater maximum rooting depth (Champoux et al 1995), a capacity to penetrate hardpans (Ray et al 1996), and a capacity to osmotically adjust to declining water availability (Lilley and Ludlow 1996). Related efforts in physiology are examining whether incorporation of those traits would result in greater extraction of water from the soil in all conditions, or whether other factors could also be involved. Oxygen supply, chemical and physical barriers, rate of stress onset, and root signals could impede water extraction under some conditions, especially in rainfed lowlands (Wade et al 1997b). Further research is required to understand root growth control and water extraction in various rice environments as well as opportunities for their genetic enhancement. Improved water extraction should also be associated with improved nutrient uptake, reduced percolation loss, and reduced accession of nitrates to groundwater. Work to use marker-aided selection for improved drought tolerance is now commencing for maximum rooting depth, hardpan penetration capacity, and osmotic adjustment.

## Opportunities for sustaining water quality

### Nutrient management

Nitrogen losses when the wet season begins will be reduced by a change to direct dry seeding because the rice should capture available nitrate before it is lost to denitrification and leaching and water is lost to evaporation and percolation (Wade et al 1998a). Further benefits to nutrient balance and levels of soil organic matter may accrue from incorporation of a legume into the dry-seeded rice system, with the effect dependent upon the duration of the dry period (Ladha et al 1996).

### Salinity control

Salinization hazard can be reduced by decreasing percolation loss and providing effective drainage facilities for leaching salt from the crop root zone. At the farm level, reduced land preparation period, shallow water depths during crop growth, and proper bund repair will reduce the risk of waterlogging and salinization. The extreme situation, found when the amount of percolation water is reduced, can be avoided by allowing farmers to grow rice only in less permeable soil (Millington 1996). A concomitant use of surface water and groundwater to control water table depth and to maintain a favorable balance of water quality from the two sources offers an opportunity for controlling irrigation-induced soil salinity development (Abrol 1987).

In acid sulfate soil areas, it is judicious to limit leaching to periods with high surface water runoff, so that acid and toxic products of the leaching process are easily transported and diluted as much as possible (van Breemen 1993). At the beginning of the rainy season, when the river discharge is low, leaching can reduce the environmental hazard to surface runoff water. Leaching acid sulfate soils with floodwater at the end of the rainy season can improve rice yields (Minh et al 1997b).

### Pest management

Research has shown unnecessary pesticide use in Asian rice culture (Heong et al 1994). In the Philippines, for example, 80% of the insecticide sprays that farmers applied were found to be unnecessary (Heong et al 1995). In Indonesia, after the introduction of integrated pest management programs and the withdrawal of pesticide subsidies, insecticide use was reduced substantially, with no decline in rice productivity (Ruchijat and Sukmaraganda 1992). Rice breeders, by applying modern biotechnology, may also succeed in developing varieties with insect and disease resistance and thus lessen dependence on the heavy use of pesticides. We may also substitute the more hazardous category chemicals with less hazardous ones without affecting crop productivity (Pingali and Rola 1995).

Via judicious water management, we can reduce herbicide use without sacrificing rice yield. Weed control in WSR is adequate with half the recommended dose of herbicide, especially when land is prepared 7–10 d between primary and secondary tillage to allow seeds to germinate after the primary tillage (Bhagat et al 1996). Shallow flooding during the first 45 d after transplanting, followed by maintenance of a saturated-soil regime for the rest of the season, achieved the same yield as conventional water management, but with more than a 30% savings in water (Table 2; Bhuiyan et al 1995).

## Conclusions

A water crisis for rice is fast approaching. We therefore need to analyze future scenarios and options to guide research directions and national water policies toward more rice production with less water.

It is tempting to assume that water efficiency in rice production will improve as water becomes a scarcer resource for rice farmers. But will things really develop that way? A recent analysis of a large number of irrigation systems in both arid and humid areas did not find any significant correlation between water scarcity and irrigation system performance (World Bank 1994). The study indicated that groundwater projects in wet areas did better than those in dry areas. As water scarcity increases, the politically and socially powerful members of the rural community may find ways to secure the limited amounts for themselves first, ignoring the needs of others in the system. In short, we do not have a rational way to prepare for the impending water shortage, to overcome it, and to minimize its effect on food production.

Demand for water delivery for the rice crop is often too high and not sustainable. Practical means of addressing the issue have not been available for public-sector irrigation systems because operating agencies did not have full control over water. Sustainable means of improving control over the resource must be found to increase water efficiency in rice irrigation systems.

Although some improvements in our capacity to handle the decreasing availability of water for rice culture seem feasible, no clear picture has emerged on how severe the present level of deterioration of water quality is and what can be expected in the future. Consciousness of water-quality problems as affected by agricultural practices, such as nitrogen and pesticide use, has just begun to grow in most Asian rice-producing countries. It will be unwise to permit water-quality-degradation processes to continue until the problem has magnified to dangerous proportions. Studies of the degree of water-quality degradation and correction options are essential.

The basic ingredients of developing and implementing water-efficient rice production systems seem to be in place now. The immediate challenge lies in tailoring these systems to suit local conditions and farming communities and, at the same time, in changing long-standing practices and operational procedures in the farm and irrigation system. A special challenge in addressing these issues is that new ideas and initiatives have to be tested without adversely affecting farmers' production or income.

## References


Abrol IP. 1987. Salinity and food production in the Indian Subcontinent. In: Jordan WR, editor. Water and water policy in world food supplies. Proceedings of the Conference, 26-30 May 1985. Texas A&M University, College Station, Texas, USA. p 109-113.

Bastiaans L, Kropff MJ, Kempuchetty N, Rajan A, Migo TR. 1997. Can simulation models help design rice cultivars that are more competitive against weeds? Field Crops Res. 51(1/2):101-111.

Bhagat RM, Bhuiyan SI, Moody K. 1996. Water, tillage and weed interactions in lowland tropical rice: a review. Agric. Water Manage. 31(1996):165-184.

Bhuiyan SI, Sattar MA, Khan MAK. 1995. Improving water use efficiency in rice irrigation through wet-seeding. Irrig. Sci. 16(1):1-8.

Castañeda AR, Bhuiyan SI. 1991. Nitrate-nitrogen concentrations in shallow groundwater underneath ricefields. Phil. J. Crop Sci. 16(2):57-62.

Castañeda AR, Bhuiyan SI. 1996. Groundwater contamination by ricefield pesticides and some influencing factors. J. Environ. Sci. Health 31:83-90.

Champoux MC, Wang G, Sarkarung S, Mackill DJ, O'Toole JC, Huang N, McCouch SR. 1995. Locating genes associated with root morphology and drought avoidance in rice via linkage to molecular markers. Theor. Appl. Genet. 90:969-981.

Cheng HH. 1990. Pesticides in soil environment: processes, impacts and modeling. Madison, Wis. (USA): Soil Science Society of America.

Dent D. 1992. Reclamation of acid sulphate soils. In: Lal R, Stewart BA, editors. Advances in soil science. New York: Springer-Verlag. 17:79-122.

De Datta SK. 1981. Principles and practices of rice production. New York: John Wiley and Sons. 618 p.

Dogra B. 1986. The Indian experience with large dams. In: Goldsmith E, Hildyard N, editors. United Kingdom: Wadbridge Ecological Center. p 201-208.

FAO/WHO (Food and Agriculture Organization/World Health Organization). 1977. Pesticide residues in food. Report of the 1976 Joint Meeting of the FAO Panel of Experts on Pesticide Residues and the Environment and the WHO Experts Group on Pesticide Residues, Rome, Italy.

Follet RF, Walker DJ. 1989. Groundwater quality concerns about nitrogen. In: Nitrogen management and groundwater protection. Amsterdam (Netherlands): Elsevier Science Publishers B.V.

Fukai S, Rajatsasereekul S, Boonjung H, Skulkhu E. 1995. Simulation modeling to quantify the effect of drought for rainfed lowland rice in northeast Thailand. In: Fragile lives in fragile ecosystems. Proceedings of the International Rice Research Conference, 13-17 Feb 1995. Manila (Philippines): International Rice Research Institute. p 657-674.

George T, Ladha JK, Garrity DP, Buresh RJ. 1994. Legumes as nitrate catch crops during the dry-to-wet season transition in lowland rice-based cropping systems. Agron. J. 86:267-273.

Ghani MA, Bhuiyan SI, Hill RW. 1989. A model to evaluate intensive vs extensive irrigation practices for rice production in Bangladesh. Agric. Water Manage. 20:233-244.

Gleick PH, editor. 1993. Water in crisis: a guide to the world's fresh water resources. New York (USA): Oxford University Press.

Gumtang RJ, Pampolino MF, Tuong TP. 1998. Groundwater dynamics and quality under intensive cropping systems. J. Exp. Agric. (In press.)

Heong KL, Escalada MM, Vo Mai. 1994. An analysis of insecticide use in rice: case studies in the Philippines and Vietnam. Int. J. Pest Manage. 40: 173- 178.

Heong KL, Escalada MM, Lazaro AA. 1995. Misuse of pesticides among rice farmers: Leyte, Philippines. In: Pingali PL, Roger PA, editors. Impact of pesticides on farmer health and the rice environment. Norwell, Mass. (USA): Kluwer Academic Publishers, and Manila (Philippines): International Rice Research Institute. p 97-108.

Ho Nai Kin, Cheng CM, Murat M, Ismail MZ. 1993. MADA's experiences in direct seeding. Paper presented at the workshop on Water and Direct Seeding for Rice, 14-16 June 1993, Muda Agricultural Development Authority, Ampang Jajar, Alor Setar, Malaysia.

Hossain M. 1995. Sustaining food security for fragile environments in Asia: achievements, challenges, and implications for rice research. In: Fragile lives in fragile ecosystems. Proceedings of the International Rice Research Conference, 13-17 Feb 1995. Manila (Philippines): International Rice Research Institute. p 3-23.

IRRI (International Rice Research Institute). 1989. IRRI toward 2000 and beyond. Manila (Philippines): IRRI.

IRRI (International Rice Research Institute). 1993. IRRI rice almanac, 1993-1995. Manila (Philippines): IRRI.

IRRI (International Rice Research Institute). 1995. Water–a looming crisis. Manila (Philippines): IRRI.

IRRI (International Rice Research Institute). 1998. Medium-term plan. Manila (Philippines): IRRI.

Khosla BK, Gupta RK, Chawla KL. 1980. Evaluating the field hydraulic conductivity and soil salinization under conditions of high water table. In: Proceedings of the international symposium on salt affected soils. Karnal (India): Central Soil Salinity Research Institute. p 256-264.

Klepper O, Hatta GM, Chairuddin G. 1990. Environmental impacts of the reclamation of acid sulphate soils in Indonesia. IARD J. 12(2):29-34.

Ladha JK, Kundu DK, Van Coppenolle G, Peoples MB, Carangal VR, Dent PJ. 1996. Legume productivity and soil nitrogen dynamics in lowland rice-based cropping systems. Soil Sci. Soc. Am. J. 60:183-192.

Lilley JM, Ludlow MM. 1996. Expression of osmotic adjustment and dehydration tolerance in diverse rice lines. Field Crops Res. 48:185-197.

Lim GS, Ong SH. 1977. Pesticide benefits and side effects. Southeast Asian workshop on pesticide management, Bangkok, Thailand.

Ludlow MM, Muchow RC. 1990. A critical evaluation of the traits for improving crop yields in water limited environments. Adv. Agron. 43:107-153.

Millington P. 1996. The basin management context. Keynote presentation at the Regional Consultation Workshop Towards a Policy for Water Resource Development and Management in the Asian and Pacific Region, The Asian Development Bank, 10-14 May 1996, Manila, Philippines.

Minh LQ, Tuong TP, van Mensvoort MEF, Bouma J. 1997a. Contamination of surface water as affected by land use in acid sulphate soils in the Mekong Delta, Vietnam. Agric. Ecosys. Environ. 61 (1): 19-27.

Minh LQ, Tuong TP, van Mensvoort MEF, Bouma J. 1997b. Tillage and water management for increasing riceland productivity in flood prone acid sulphate soil areas of the Mekong Delta, Vietnam. J. Soil Tillage 42:l-14.

Murray-Rust DH, Snellen WB. 1993. Irrigation system performance assessment and diagnosis. IIMI, ILRI, and IIHEE. 148 p.

My TV, Tuong TP, Xuan VT, Nghiep NT. 1995. Dry seeding rice for increased cropping intensity in Long An Province, Vietnam. In: Denning GL, Xuan VT, editors. Vietnam and IRRI: a partnership in rice research. Manila (Philippines): International Rice Research Institute, and Hanoi (Vietnam): Ministry of Agriculture and Food Industry, p 111-122.

Pascua SR, Ladha JK, Ventura W, Agustin EO, Valencia DV, Marcos TF, Sta. Cruz PC, Obien SR. 1997. Yield trends and apparent nutrient balances in intensified and diversified cropping systems of Ilocos Norte, Philippines. Exp. Agric. (In press.)

Pingali PL, Rola AC. 1995. Public regulatory roles in developing markets: the case of pesticides. In: Pingali PL, Roger PA, editors. Impact of pesticides on farmer health and the rice environment. Manila (Philippines): International Rice Research Institute. p 391-412.

Postel S. 1989. Water for agriculture: facing the limits. World Watch Paper 93. Washington, D.C. (USA): World Watch Institute.

Ray JD, Yu L, McCouch SR, Champoux M, Wang G, Nguyen HT. 1996. Mapping quantitative trait loci associated with root penetration ability in rice (*Oryza sativa* L.). Theor. Appl. Genet. 92:627-636.

Ruchijat E, Sukmaraganda. 1992. Material integrated pest management in Indonesia: its successes and challenges. In: Ooi P, Lim G, Ho T, Manulo P, Waage J, editors. Integrated pest management: the Asia-Pacific region. CABC and ADB. p 329-347.

Saleh AFM, Bhuiyan SI. 1995. Crop and rainwater management strategies for increasing productivity of rainfed lowland rice systems. Agric. Sys. 49:259-276.

Sarkarung S, Singh ON, Roy JK, Vanavichit A, Bhekasut P. 1995. Breeding strategies for rainfed lowland ecosystem. In: Fragile lives in fragile ecosystems. Proceedings of the International Rice Research Conference, 13-17 Feb 1995. Manila (Philippines): International Rice Research Institute. p 709-720.

Sarma PBS. 1986. Water resources and their role in food production. In: Swaminathan MS, Sinha SK, editors. Global aspects of food production. Oxford, Riverton, N.J. (USA): Tycooly International. p 171-198.

Tabbal DF, Lampayan RM, Bhuiyan SI. 1992. Water-efficient irrigation technique for rice. In: Murty VVN, Koga K, editors. Soil and water engineering for paddy field management. Proceedings of the International Workshop on Soil and Water Engineering for Paddy Field Management, Bangkok, Thailand, 28-30 Jan 1992. Bangkok: Asian Institute of Technology. p 146-159.

Tuong TP, Cabangon RJ. 1996. Reducing bypass flow during land soaking of cracked rice soils. In: Kirichoff G, So B, editors. Management of clay soils in rainfed rice-based cropping systems. Proceedings of a workshop held at the Bureau of Soil and Water Management, Quezon City, Philippines, 20-24 Nov 1995. Proceedings No. 70. Canberra (Australia): Australian Centre for International Agricultural Research. p 237-242.

Tuong TP, Wopereis MCS, Marquez J, Kropff MJ. 1994. Mechanisms and control of percolation losses in irrigated puddled rice fields. Soil Sci. Soc. Am. J. 58:1794-1803.

Valera A. 1977. Field studies on water use and duration for land preparation for lowland rice. Ph.D. dissertation. University of the Philippines at Los Baños, Philippines.

van Breemen N. 1993. Environmental aspects of acid sulphate soils. In: Dent DL, van Mensvoort MEF, editors. Selected papers on the Ho Chi Minh City symposium on acid sulphate soils. International Institute for Land Reclamation and Improvement Publication No 53. Wageningen (Netherlands). p 391-402.

Viets FG Jr, Hageman RH. 1976. Factors affecting the accumulation of nitrate in soil, water, and plants. Agriculture Handbook No. 413. Washington, D.C. (USA): Agricultural Research Service-United States Department of Agriculture.

Wade LJ, Ladha JK. 1995. The fate of organic matter and nutrients in lowland rice systems. In: Lefroy RDB, Blair CJ, Craswell ET, editors. Soil organic matter management for sustainable agriculture. ACIAR Proceedings Number 56. Canberra (Australia): ACIAR. p 115-119.

Wade LJ, George T, Ladha JK, Singh U, Bhuiyan SI, Pandey S. 1998a. Opportunities to manipulate nutrient-by-water interactions in rainfed lowland rice systems. Field Crops Res. 56:93-112.

Wade LJ, Moya TB, Pantuwan G, Regmi KR, Samson BK. 1998b. Research at IRRI on rice root systems for drought resistance. In: Morita S, Abe J, editors. Perspective on ideotype of rice root system. Singapore: World Scientific Publishing. (In press.)

Wickham TH, Sen LN. 1978. Water management for lowland rice: water requirements and yield response. In: Soils and rice. Manila (Philippines): International Rice Research Institute. p 649-669.

World Bank. 1994. A review of World Bank experience in irrigation. Report No. 13676. Washington, D.C. (USA): World Bank. 126 p.

## Notes

*Authors' address:* International Rice Research Institute, P.O. Box 933, Manila, Philippines. s.bhuiyan@cgnet.com t.p.tuong@cgnet.com l.wade@cgnet.com

*Citation:* Dowling NG, Greenfield SM, Fischer KS, editors. 1998. Sustainability of rice in the global food system. Davis, Calif. (USA): Pacific Basin Study Center, and Manila (Philippines): International Rice Research Institute.

CHAPTER 12

# Securing the future of intensive rice systems: a knowledge-intensive resource management and technology approach

L.M.L. Price and V. Balasubramanian

Scientific achievements in increasing yields have been fast and profound in Asia's intensive rice systems, but farmers' knowledge and corresponding practices have not kept pace, particularly in disease, pest, nutrient, and water management. Knowledge-intensive resource management and technology can be used to fine-tune farmer management to enhance profitability and environmental protection in high-productivity systems. This paper identifies, defines, and discusses two strategies: (1) KIT-P, knowledge physically embedded in machines and instruments that provide field-level information to farmers, and (2) KIT-H, knowledge embedded in the farmers themselves and composed of information directly linked to cognition and acquired through a process of learning and experimentation. Making more knowledge and information available to farmers is one way of addressing the problems of resource depletion in both quantity and quality, of degradation of the environment, and of increased health risks caused by lack of appropriate knowledge in managing changes in cropping systems. Knowledge-intensive approaches are expected to serve farmers in decision making and in enhancing precision as they come to terms with the Green Revolution of the past and face future challenges.

International agricultural research has generated technologies that have changed the face of rice production in Asia. No longer do we hear the predictions of massive starvation in Asia that were given prior to the Green Revolution. The annual productivity growth of rice, the staple food of Asia, kept pace with population growth from the 1960s to the mid-1980s (Herdt and Capule 1983, Dalrymple 1986, Hossain and Fischer 1995). The Green Revolution strategy, started in the early 1960s, was based on the use of modern rice varieties, assured irrigation, and subsidies for fertilizers, pesticides, and farm equipment. It provided food security to people for more than three decades and minimized the extension of food crop cultivation to ecologically fragile, marginal lands. But we are only beginning to understand that intensive rice-cropping systems and crop and resource management technologies used for the Green Revolution may have adversely affected the environment.

Although IRRI continues to work to increase productivity to meet predicted demands for rice through plant breeding and biotechnology, its rice scientists also realize that they have reached a new frontier that requires more expertise on the part of the farmer. Environmentally sound management practices can greatly reduce stress on the resource base, raise farm profits, and improve farmer health and productivity. New knowledge-intensive management practices and technologies are most urgently needed where traditional knowledge has not been applicable to methods of intensive rice production from the Green Revolution. Farmers are unable to manage nutrient inputs to meet crop and soil needs, are erroneously applying insecticides, and are ill-equipped to understand and control diseases such as blast and tungro. In addition, farmers rapidly change their rice cultivation systems in response to higher costs, particularly labor. The labor savings of direct-seeded rice bring issues of weed management and herbicide use to the foreground.

The future of intensive rice systems that looms before us is one of ever-decreasing natural and human resources. Scientific achievements in increasing yields have been fast and profound in Asia's intensive rice systems, but farmers' knowledge and corresponding practices have not kept pace, specifically in disease, pest, nutrient, and water management. This paper calls for increased attention to knowledge-based management and technology application at the farm level to tackle the problems of highly productive agriculture. We identify key productivity and environmental considerations, explore knowledge-intensive approaches for crop management, and suggest directions that will help to develop strategies to generate and diffuse knowledge-intensive resource management approaches and technologies.

## Environmental degradation and dwindling resources

Intensive cropping methods pursued in the past three decades have led to a significant depletion of resources both in quantity and quality, degradation of the environment, and increased health risks to producers and consumers (Cassman and Pingali 1995, Gardner 1996). The long-term implications of using chemical inputs and regarding them as routine, prophylactic practices were not known at that time. The Green Revolution and government and development agencies focused mainly on the goal of increasing yields of target crops with improved varieties and routine application of inputs at recommended rates.

### Nutrients

Soil degradation is caused by nutrient imbalance (deficiency or toxicity), salinity/alkalinity, waterlogging, subsoil compaction, and declining organic matter quality and soil N supply (Cassman et al 1993, Kundu et al 1995). Because nutrient management needs are predominantly farm- and field-specific, knowledgeable decisions on how much and when to apply nutrients are required. Decision-making success is typically expressed in crop yields.

Rice yield response follows a diminishing return function with increasing N application. Yields could decrease further because of lodging and increased incidence of pests and diseases at high N levels. Good crop and water management on research stations has resulted in higher fertilizer N (50–60% efficiency) (Cassman et al 1994), but such precision management practices must be economically viable when all costs are considered.

To obtain the projected grain yield of 8 t ha$^{-1}$ in irrigated rice by the year 2025, it is necessary to apply 280 kg N ha$^{-1}$ at 33% fertilizer N recovery efficiency (Cassman and Pingali 1995). This means that urea fertilizer applied to irrigated rice in Asia would increase from 15.5 to 43.6 million t—nearly a 300% increase in N for a 63% increase in yield. By increasing fertilizer N recovery efficiency to 50%, it is possible to reduce the N application rate from 280 to 187 kg ha$^{-1}$ and the urea fertilizer need from 43.6 to 29.1 million t—still a 200% increase in fertilizer N application for a 63% increase in yield (Cassman and Pingali 1995).

Governments in Asia are moving away from fertilizer subsidies—a practice begun in the 1970s. Although the subsidy structure may have accounted for excessive growth in fertilizer inputs to intensive rice systems, farmers' current decisions on what can profitably be used in crop production may be guided more by fertilizer market prices. The situation is essentially the same because decision making on inputs is driven by price and external recommendations. Efficient fertilizer use will produce healthy plants that are less vulnerable to pests and diseases and to lodging. Optimal crop management requires farmer knowledge of matching inputs to crop production needs (Pingali et al 1995).

The overuse or improper use of nutrient inputs is highly damaging to crops and the environment (FFTC 1994). Excess nitrates pollute not only the soil and groundwater but also the produce itself. Nitrous oxide released from denitrification of nitrates pollutes the air. Recent studies indicate increased nitrate levels above the permissible limit of 10 ppm $NO_3$-N in well water because of excess fertilizer application to the pepper crop after rice in Batac, northern Philippines (J.K. Ladha, IRRI, Philippines, 1996, personal communication). Nitrate in food or drinking water is a hazard to human health. Therefore, to minimize health risks, new methods or products must be developed to achieve a more efficient use of nutrient sources. Efficient fertilizer use will minimize water pollution by nitrates and phosphates, and will reduce the accumulation of free nitrates in food.

## Pesticides

Likewise, pesticide inputs are historically not matched to crop needs in intensive systems. The recommendation for crop protection set in the 1970s, consisting of prophylactic calendar-based spraying, was not based on actual pest infestations and crop loss calculations. This recommendation has been adopted by farmers as a standard procedure; in many places, calendar-based chemical pest control, particularly for insects, is still being recommended. Such an approach to crop protection undermines environmental integrity, host-plant resistance, human health, and, ultimately, the profitability of the farming enterprise (Heong et al 1995, Widawsky 1996, Price 1995, Rola and Pingali 1993).

Optimal use of inputs is a growing concern. Factors other than meeting crop needs affect optimum productivity and farmer welfare. Health effects from pesticide exposure include a whole range of medical problems from acute pesticide poisoning to symptoms of ill health from long-term exposure (Pingali et al 1992, Rola and Pingali 1993). Rola and Pingali (1993) conclude that "prolonged and frequent exposure to pesticides impairs farmers' health and hence their productivity. The more frequent the insecticide applications, the higher are the health costs, treatment costs, and opportunity cost of time lost. Explicit accounting for health costs substantially raises the cost of using pesticides. The value of the crop lost to pests is invariably lower than the cost of treating pesticide-caused [human] disease. When health costs are factored in, the natural control ('do nothing') option is the most profitable and useful pest control strategy."

### Conserving resources

Increasing input efficiency not only minimizes environmental pollution and health risks but also conserves the nonrenewable sources of fertilizers, such as fossil fuels and minerals. At the projected rate of consumption, known oil reserves will limit food production in 50 yr, phosphorus deposits will be depleted in 90 yr, and other minerals (K, Mg, trace elements) will become increasingly scarce. Technologies that recycle nutrients efficiently and maximize biological N fixation have to be used increasingly to prolong the availability of these nonrenewable resources.

## A knowledge-intensive approach defined

Two primary knowledge-intensive crop and resource management approaches exist: (1) knowledge imbedded in machines/instruments, and (2) knowledge imbedded within farmers themselves. The first encompasses physical technology—in which the knowledge or expertise to enhance decision making is imbedded in the physical technology itself, termed here "knowledge-intensive technology-physical" (KIT-P). The second is knowledge as it is held by people—which is directly linked to cognition and is acquired and retained through a process of learning and experimentation (KIT-H). Information is narrower in scope than knowledge and implies a random collection of material rather than an orderly synthesis. Knowledge is thus a system of cognition and interpretation; it is dynamic in that it builds upon itself empirically through trial and error. While knowledge acts as a foundation for building upon, it is also a foundation for interpretation; it acts as a filter through which we interpret our new observations. KIT-P provides farmers with information to enhance precision, but the data generated must still be interpreted so that appropriate action can be taken. KIT-H provides knowledge, but an orderly cognitive synthesis must take place in the minds of farmers if KIT-H approaches are to be valid.

Traditional research produced the Green Revolution seed technology, but seed technology is becoming increasingly complex. Host-plant resistance (HPR), for example, requires a different management method. Studies have shown that the message of resistance has not filtered down to farmer behavior and farmers continue to spray resistant varieties. Although HPR is an effective substitute (economically) for pesticides, there is increasing evidence that HPR must be accompanied by knowledge as a substitute for pesticides (Widawsky 1996).

### Knowledge imbedded in physical technology (KIT-P)

KIT-P is distinct from other modem technologies in that it enhances decision making through information, whereas other modern technologies, such as seed technology, although the product of much scientific knowledge, do not. An excellent example of KIT-P is the Ag Leader Yield Monitor 2000 developed by Ag Leader Technology in Ames, Iowa (USA). This KIT harvester combines a digital device, global positioning system, and transducer behind a plate. The amount harvested is continuously measured by the force striking the plate and values are fed into the processor. Values are corrected for factors that include the speed of the combine and moisture content of the crop. One acre of land might be broken up into 500 measurement units. Farmers can then identify sections of their fields that have production shortfalls. With this information, they can call in outside assistance for soil testing, make investment decisions on upgrading selected field areas, and use their data to validate claims made by commercial enterprises such as projected yields of seed by private-sector enterprises or government agricultural extension agents (Hapgood 1995).

### Knowledge imbedded in human beings (KIT-H)

KIT-H approaches to resource management are concerned with imparting learning that fits the structured cognition of farmers in an orderly and synthetic fashion. In building knowledge-intensive approaches to resource management, scientists are operating on principles in a scientific tradition, one with explicit notions and methods of verification of cause-and-effect relationships. Farmers—within their various cultural perspectives and traditions—also have understandings of cause-and-effect relationships that must be addressed in any knowledge-intensive approach.

The science of building knowledge involves theory, fact, observation, and probability. Western science has provided us with the documented history of the importance of a framework within which to interpret facts. The theoretical context within which the facts are interpreted will ultimately influence interpretations and conclusions drawn from experiments. Observations and facts are not sufficient—contextualizing theory must be included. Before the introduction and acceptance of statistical probability, facts and observations were at the mercy of equally plausible interpretations. Science no longer seeks the certainty of predicting all instances but uses statistics as a tool to gauge the degree to which a theory will give us predictive power.

When we develop a knowledge-intensive approach, we are in essence drawing on a great tradition and the lessons learned along the way. Transferring only one component of the scientific process—for example, only facts or observations—may be at the expense of full absorption and sustainability of knowledge.

Integrated pest management with the farmer field school approach (IPM FFS) is an example of KIT-H. The pest management package, however, includes both information and knowledge. Although information may be easily incorporated, knowledge of crop management must compete with knowledge systems already in place. The IPM FFS approach involves a system in which observations are made, facts are highlighted, and observations and facts are placed in a framework of ecological theory. Farmers also learn about probability of infestations (through monitoring techniques) and yield loss (economic thresholds). Social reinforcement of the learning process occurs through the learning interactions of FFS students.

### Combining physical technology and human learning: the chlorophyll meter method for better timing of N application

Significant spatial and temporal crop yield variations are common in any field because of variations in microclimate, soil type, soil flora and fauna, organic matter content and quality, nutrient status, drainage, pest and disease incidence, and weed infestation (Hapgood 1995). Hapgood maintains that the same input will not produce the same output from one year to the next, nor do any two fields on one farm produce the same yield in the same year.

IRRI researchers are developing improved techniques to predict soil N supply and in-season plant N status. Peng et al (1995) adapted the chlorophyll meter method to measure the leaf N status of rice and to synchronize N application with crop demand. The meter readings (also called SPAD values) are calibrated with rice leaf N concentrations and critical meter values are established to determine the need for N application. For example, 35 is the critical SPAD value for transplanted semidwarf indica varieties in irrigated systems during the dry season; whenever the meter reading falls below 35, a topdressing of 30-40 kg N $ha^{-1}$ is recommended. The chlorophyll meter can be used to handle soil variability by adjusting N application to crops, based on variable soil N supply and crop demand in different fields or different parts of a large farm. It can also be used to diagnose soil or crop problems that affect plant N uptake and yield.

Several factors—such as cultivar, plant population, stage of growth, and biotic and abiotic stresses that cause leaf chlorosis—affect chlorophyll meter readings (Peterson et al 1993, Turner and Jund 1994). Therefore, the SPAD meter should be calibrated on the basis of cultivar group, system of crop establishment, plant density, and environmental conditions prevalent in each location. If meter readings are properly calibrated according to cultivar group under local conditions, the chlorophyll meter can be a good tool for fine-tuning the N fertilization of a crop and for correcting N deficiency within the same season. For proper calibration, an education component to accompany the physical technology must be developed.

National agricultural research systems are evaluating the chlorophyll meter method in farmers' fields. Early results indicate that the method works well on transplanted rice; the critical SPAD value may require some adjustment for different seasons and systems of crop establishment (e.g., direct-seeded rice) (Turner and Jund 1994, Balasubramanian et al 1998).

### Measuring KIT-H in farmers

The popularity of IPM FFS as a KIT-H approach continues to spread across the globe. The challenge lies in conducting empirical investigations and developing measures of how knowledge is absorbed, acted upon, and transferred on a farmer-to-farmer basis. Knowledge as it is expressed in farmer cognition and decision making can be measured with a combination of ethnosemantic elicitation, analysis of cognitive domains (factual knowledge), and expert systems/knowledge-based systems to model decision making. (Knowledge-based systems computer software allows for both absolute and probabilistic statements, reasoning from the rule antecedent or the consequence ["if" and "then" in sequence]. Ethnosemantic elicitation is a well-tested tool used in anthropology by ethnobotanists and ethnozoologists to capture the structure of cognitive domains.) Procedural knowledge is contained in the rules, whereas the values of the variables included in the rules represent the factual knowledge (Guillet 1989). Together, procedural and factual knowledge systems represent one possible strategy for revealing the relationship between knowledge and action on the part of farmers. Locating values representing cognitive absorption, decision making, and transfer is a high priority and is needed to develop accurate measures of returns to investment and techniques for analyzing the economic impact of knowledge and knowledge transfer.

## The process of knowledge incorporation

The transfer of knowledge based on scientific principles aimed at altering farming practices requires a good fit between the knowledge system of the farmers and that of the scientists. If new components were added to the existing knowledge system and if these were couched in familiar terms, there would be latitude for experimentation on the local level that could eventually develop into a functional fit. A scientific (versus local or indigenous) interpretation may not be feasible because of the high cost of education and uncertain desirability of replacing the foundation of indigenous practices, many of which may be environmentally sound.

Much of what we currently see as mismanagement in intensive rice systems is the farmer response to a lack of appropriate knowledge in managing Green Revolution changes in cropping systems. The "blanket recommendation approach" gave farmers information without understanding—it provided information but did not expand knowledge. This led to the continuation of practices deemed scientifically unsound on the basis of contemporary research. Farmers continue to engage in what we now know as dangerous behavior (in terms of health, productivity, and environmental protection). But farmers' behavior is consistent with their assessments of the probability of success, given their interpretation of the options available. These judgments are embedded in and filtered through their knowledge base coupled with information that remains outside that base. From their perspective, farmers act to enhance their probability of obtaining success.

Nazarea (1996) provides evidence that farmers slowly lost confidence in indigenous knowledge (the ethnoscientific knowledge base) during the Green Revolution accompanied by a desire to manage their crops on scientific principles. It is therefore probable that (1) these farmers have become more reliant on external recommendations and (2) appropriate indigenous/local knowledge is absent or farmers are not willing to use the indigenous knowledge that is appropriate to managing intensive systems.

Documenting actual decision making is necessary to bring to the foreground constraints to the implementation of knowledge if absorption is present. Economic constraints may force farmers to act in ways inconsistent with their environmental/agronomic knowledge base. For example, labor demand for monitoring environmental phenomena and calculating thresholds is high. Labor is a common production constraint in intensive rice systems and it may constrain the implementation of knowledge-intensive crop management practices. It is therefore important to evaluate impact with instruments that uncover these distinctions in decision making.

## Support systems

Systematic attempts to develop, test, transfer, and track knowledge and knowledge-intensive physical technologies need multidisciplinary planning and strategic research, government support, and farmer participation. Diffusion of knowledge-intensive technologies to farmers is more difficult than distribution of improved seeds of new varieties. Several institutions and organizations are involved in this process—education and training groups, extension services, banks for credit, input suppliers, machinery companies and contractors, traders, market outlets, rural infrastructure, and policy-making bodies. All have to perform effectively in a coordinated manner to maximize adoption of knowledge-intensive management technologies.

### Training and education

Wherever feasible, farmers should be involved as opinion givers or as active partners in the generation, adaptation, and diffusion of new knowledge and technologies. Farmer participation and contributions are considerable in evaluating a new knowledge or technology. For a completely new KIT-P, they play a consultative role, providing a valuable input. We can reinforce the individual farmer's opinions and assessments in group discussions. Wherever possible, working with farmer groups or associations is better. KIT-H can also be best served with a model that incorporates active learning among farmers and a social group to reinforce learning.

Farmers will need support for various combinations of KIT-P and KIT-H. For example, pheromone traps are being tested to control yellow stem borers in rice (K. Krishnaiah, Directorate of Rice Research, Hyderabad, India, 1996, personal communication). Farmers should therefore know about the life cycle of the yellow stem borer, the threshold levels of damage, or how borers are attracted by pheromones before they can correctly apply the pheromone technology in their fields. Once the principles are well understood, farmers themselves can make minor changes in the application of a technology to increase its effectiveness. Similarly, farmers must be educated on the proper use of pest- and disease-resistant rice varieties before such varieties are deployed.

### Institutional support

Availability of agricultural credit, timely supply of inputs, availability and quality of contract services and machinery for different farm operations, and repair and maintenance services in rural areas will influence the rate of adoption of new KIT-P. In promoting new machines to Asian farmers, it is important to implement certain steps to increase and sustain adoption—standardize the new machines and spare parts to assure quality, provide a warranty for specified periods, train farmers in the correct use and maintenance of the machines, assure after-sales service and follow-up inspections and advice, and provide repair services in rural areas within easy reach of farmers. Similar iterative steps have to be developed and tested for knowledge-intensive resource education (KIT-H).

### Policy support

The lack of a mechanism to take promising technologies to the field for farmer evaluation and the absence of government action plans to mobilize necessary institutional and policy support often hinder farmer adoption (Tandon 1989). The national bureaucracy and government policies must be favorable to the process of technology assessment, adaptation, and promotion. Some countries have realized the importance of farmer assessment and use of new technologies in achieving impact on food production. They are therefore developing technology assessment units for on-farm evaluation and adaptation of new technologies in target areas. A good example is Indonesia, where 17 assessment institutes for agricultural technologies are being developed to undertake location-specific adaptive research and technology evaluation.

## Conclusions

Intensive cropping methods pursued in the past three decades have led to a significant depletion of resources in both quantity and quality, degradation of the environment, and increased health risks to producers and consumers. Much of what we currently recognize as mismanagement in intensive rice systems is a farmer response to the lack of appropriate knowledge on managing Green Revolution changes in cropping systems. The "blanket recommendation approach" gave farmers information without understanding—it provided information but did not expand knowledge.

This paper has examined the potential of knowledge-intensive technologies for enhancing appropriate precision management of intensive rice production systems. It stresses the importance of distinguishing between physical technologies in which knowledge is embedded in machines and instruments (KIT-P) and knowledge that is embedded within farmers as human beings (KIT-H). Both approaches require systematic multidisciplinary planning and strategic research, government support, and farmer participation in attempts to develop, test, transfer, and track knowledge and knowledge-intensive physical technologies.

The potential for knowledge-intensive technologies is tremendous—not only for the protection of crops, natural resources, and human health of present and future generations of farmers but also for empowering farmers to validate claims of commercial agricultural enterprises and extension alike.

## References


Balasubramanian V, Morales AC, Cruz RT, Abdul Rachman S. 1998. On-farm adaptation of knowledge-intensive nitrogen management technologies for rice systems. Nut. Cyc. Agroecosys. (In press.)

Cassman KG, Kropff MJ, Gaunt J, Peng S. 1993. Nitrogen use efficiency of rice reconsidered: what are the key constraints? Plant Soil 155/156:359-362.

Cassman KG, Kropff MJ, Yan ZD. 1994. A conceptual framework for nitrogen management of irrigated rice in high-yield environments. In: Virmani SS, editor. Hybrid rice technology: new developments and future prospects. Manila (Philippines): International Rice Research Institute. p 81-96.

Cassman KG, Pingali PL. 1995. Intensification of irrigated rice systems: learning from the past to meet future challenges. GeoJoumal 35(3):299-305.

Dalrymple DG. 1986. Development and spread of high-yielding rice varieties in developing countries. Washington, D.C. (USA): Metrotec, lnc.

FFTC (Food and Fertilizer Technology Center). 1994. Fertilizer use and sustainable food production. FFTC Newsletter 104(June 1994):4-5.

Gardner G. 1996. Preserving agricultural resources. In: Brown LR et al, editors. State of the world 1996. New York (USA): World Watch Institute and W.W. Norton and Company. p 78-94, 208-213.

Guillet D. 1989. Expert-systems applications in anthropology. Anthropol. Quart. 64(2):59-67.

Hapgood F. 1995. High-tech harvest. Inc. Technol. 3:52-55.

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 farmer health and the rice environment. Massachusetss (USA): Kluwer Academic Publishers.

Herdt RW, Capule C. 1983. Adoption, spread, and production impact of modern rice varieties in Asia. Manila (Philippines): International Rice Research Institute.

Hossain M, Fischer KS. 1995. Rice research for food security and sustainable agricultural development in Asia. GeoJoumal 35(3):286-298.

Kundu DK, Ladha JK. 1995. Enhancing soil nitrogen use and biological nitrogen fixation in wetland rice. Exp. Agric. 31:261-277.

Nazarea VD. 1996. Ethnoecology of the Manupali watershed. Unpublished Phase I Report of the Ethnoecology of the Manupali Watershed Project. SANREM CRSP, University of Georgia, Georgia Station, Griffin, Georgia, USA.

Peterson TA, Blackmer TM, Francis DD, Schepers JS. 1993. Using a chlorophyll meter to improve N management. A Nebguide in Soil Resource Management: D-13, Fertility. Lincoln, Neb. (USA): Cooperative Extension, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln.

Pingali PL, Hossain M, Pandey S, Price L. 1995. Economics of nutrient management in Asian rice systems: toward increasing knowledge intensity. Manila (Philippines): International Rice Research Institute.

Pingali PL, Marques CB, Palis FG. 1992. Farmer health impact of long-term pesticide exposure: a medical and economic analysis for the Philippines. Paper presented at a workshop on Measuring the Health and Environmental Effects of Pesticides, 30 March-3 April 1992, Bellagio, Italy.

Price LML. 1995. IPM "no early spray" farmer practice: farmer attitudes toward natural resource exploitation of rice field flora and fauna in the Philippines. Manila (Philippines): International Rice Research Institute.

Rola A, Pingali PL. 1993. Pesticides, rice productivity, and farmers' health. Manila (Philippines): International Rice Research Institute.

Tandon HLS. 1989. Urea supergranules for increasing nitrogen efficiency in rice: an overview. In: Kumar V, Shrotriya GC, Kaore SV, editors. Soil fertility and fertilizer use. Vol. III. Urea supergranules for increasing nitrogen use efficiency. New Delhi (India): Indian Farmers Fertilizer Cooperative. p 10-22.

Turner FT, Jund MF. 1994. Assessing the nitrogen requirements of rice crops with a chlorophyll meter method. Austr. J. Exp. Agric. 34:100l-1005.

Widawsky D. 1996. Rice yields, production variability, and the war against pests: an empirical investigation of pesticides, host-plant resistance and varietal diversity in China. Ph.D. dissertation. Stanford University, Stanford, California, USA.

## Notes

*Authors' addresses:* L.M.L. Price, Wageningen Agricultural University, Wageningen, The Netherlands; V. Balasubramanian, International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines. lisa.leimar-price@alg.vsl.wau.nl v.balasubramanian@cgnet.com

*Citation:* Dowling NG, Greenfield SM, Fischer KS, editors. 1998. Sustainability of rice in the global food system. Davis, Calif. (USA): Pacific Basin Study Center, and Manila (Philippines): International Rice Research Institute.

CHAPTER 13

# Rice and the global environment

R. Wassmann, T.B. Moya, and R.S. Lantin

The productivity and sustainability of natural resources ultimately depend on favorable climatic conditions that are currently being altered by human activities. The key process for changing the atmospheric environment is the combustion of fossil fuels, but agricultural activities are also associated with the release of trace gases that affect the radiation balance of the Earth. The ambivalent role of agriculture, one of the most important sectors affected by global change as well as one of the contributors to a changing environment, has prompted IRRI to investigate the interaction of rice cultivation and changing climate. Irrigated rice production at ambient growth temperature (25 °C) will benefit from increased atmospheric $CO_2$. Increased rates of $CO_2$ assimilation and decreased rates of maintenance (dark) respiration at elevated $CO_2$ result in increased plant biomass accumulation. Grain yield also increases with rising atmospheric $CO_2$ concentration. Concomitant temperature increases, however, could entail substantial losses in future yield because rice yields are extremely sensitive to temperature increases during the grain-filling stage, which can lead to abundant spikelet sterility. The coupling of crop models to future climate scenarios for the main riceg-rowing areas has given diverging results, from an 11% increase to a 12% decrease, depending on the model and scenario. The most significant contribution by rice fields to global change stems from the emission of the greenhouse gas methane. Methane formation in wetland rice fields is an important component of carbon cycling in the predominantly anaerobic soils. The quantity of methane emitted to the atmosphere is regulated by inherent soil and climate properties as well as agricultural practices. The shift from organic manure to mineral fertilizers substantially reduces methane emission. Likewise, the flux is reduced by intermittent drying of soils. New, high-yielding cultivars also reduce methane emission compared with traditional varieties. These findings help identify promising strategies to mitigate methane emission without yield losses, but they still have to be corroborated and improved by field experiments.

In recent years, public discussion on environmental issues has largely focused on the effects caused by enhanced concentrations of trace gases in the atmosphere. The recognition of a fundamental anthropogenic effect on the atmospheric composition and radiation balance of the Earth is gaining more and more acceptance in the scientific community. The detection of mechanisms leading to ozone destruction by chlorofluorocarbons (CFCs) in the stratosphere was recently acknowledged by the Nobel

Prize committee; the effect of greenhouse gases on the global climate was thoroughly reassessed and confirmed by an independent group of scientists, the Intergovernmental Panel on Climate Change (IPCC 1990, 1992). But climatic parameters such as temperature are characterized by pronounced spatial variability and genuine dynamics in different time scales. The relatively short time span of available observations impedes an ultimate proof of ongoing global warming, but indications to corroborate an anthropogenic impact on the global environment are compelling enough to urge against complacency.

The carbon dioxide ($CO_2$) level in the atmosphere has increased by approximately 32% from the preindustrial concentration of 270 ppm to a current concentration of 335–360 ppm (IPCC 1990). As the world population increases and the demand for energy rises, increased burning of fossil fuels will continue to drive levels of atmospheric $CO_2$ upward. The IPCC "business-as-usual" scenario predicts that atmospheric $CO_2$ concentrations will rise to 530 ppm by the year 2050 and could exceed 700 pprn by 2100 (IPCC 1990). This increase will significantly affect the physiological basis of plant production. The increasing ultraviolet-B (UV-B) exposure caused by ozone depletion in the stratosphere poses a further threat of unknown dimension to the productivity of agricultural systems.

Since 1991, IRRI has been examining the impact of climate change on rice cultivation as well as the specific contribution of rice fields to the global budget of greenhouse gases (Neue et al 1995). These studies include different approaches at various levels including the physiological base of rice plants and the microbial community, element cycling in rice ecosystems, and regional and global trends in rice yields under a changing climate. Such interdisciplinary efforts are indispensable for sound decisions and technology development to cope with the food demand within the coming decades and beyond.

## Agriculture in a changing global environment

The increase in $CO_2$ concentration is the key part of the greenhouse effect, accounting for approximately 50% of the projected increase in mean surface temperature (IPCC 1990). The imbalance of global sources and sinks in the atmospheric $CO_2$ budget is caused primarily by combustion of fossil fuels. Net releases of $CO_2$ by the agricultural sector are mainly related to land use changes, such as deforestation. Continuous cropping systems such as rice cultivation encompass high fluxes of $CO_2$, but input and output are balanced in sustainable production (Bronson et al 1998). Changes in soil organic carbon (C) (caused by intensified use of fertilizers), however, have a large potential to sequester C from the atmosphere (Cassmann et al 1995), although the significance of this $CO_2$ sink is still unknown.

The major contribution of rice fields to the greenhouse effect derives from the emission of methane ($CH_4$), which is ultimately linked to the submergence of soils. Nitrous oxide ($N_2O$), another greenhouse gas, is emitted from virtually all cropping systems with high nitrogen (N) inputs, including intensive rice cultivation (Rennenberg et al 1992). In spite of an increasing number of emission records, estimates of global emissions of greenhouse gases are still tentative. The broad range of these estimates prevents a definite assessment of rice cultivation's part, and thus the amount that modified rice cultivation might curtail greenhouse gas emissions on a global scale.

The need to increase rice production in the near future is imperative. Strategies to reduce greenhouse gas emissions improve the nutrient and C balance and therefore represent one component of advanced resource management in rice fields. In countries where rice cultivation predominates, rice research could play a crucial role in developing feasible mitigation strategies on a national level, a goal stipulated in the United Nations Framework Convention on Climate Change. But the largest share of historical and current greenhouse gas emissions has come from developed countries and from the energy sector. Concerted efforts for the widest possible cooperation are therefore essential to forestall changes in the global environment and possible effects on agricultural production.

## Growth and yield response of rice to enhanced $CO_2$ concentration

The projected increase in $CO_2$ concentration will significantly affect the physiological basis of plant production. Most plants grow under suboptimal levels of $CO_2$ to achieve maximum photosynthetic capacity. But the beneficial effect of higher $CO_2$ levels on plant growth may be outweighed by concomitant changes in other environmental factors (Rosenzweig and Parry 1994). Global increases in $CO_2$, along with other trace gases such as $CH_4$ and $N_2O$, will trap outgoing thermal radiation and lead to higher temperatures at the Earth's surface. Therefore, emphasis has to be given to the synergistic effects of $CO_2$ and temperature on crop growth, weed competition, and water demand.

### Photosynthesis and respiration

Figure 1 shows the leaf photosynthetic rate of IR72, which was grown in flooded fields from germination to maturity under different temperature regimes and $CO_2$ concentrations. The photosynthetic rates of plants exposed to elevated $CO_2$ levels (ambient +200 and ambient +300 ppm of $CO_2$) exceeded the rates of plants grown in ambient air by 35–60%, whereas the $CO_2$ increases of 200 and 300 ppm did not show significant differences. Higher temperature resulted in higher photosynthetic activity until flowering.

Plants use photoassimilates to build up structural biomass, but a portion of the assimilates is allocated to respiration. Respiration supplies the energy to maintain biochemical and physiological processes of growth and development. In respiration models, these functions are divided into two components—some respiration is associated with the maintenance of existing biomass and some with the synthesis of new tissue (Baker et al 1992, Kropff et al 1995). Ziska and Bunce (1993) found that maintenance respiration decreased at higher $CO_2$ levels, but the reasons for this phenomenon are not clear. Plants growing at high $CO_2$ may be constructing and maintaining

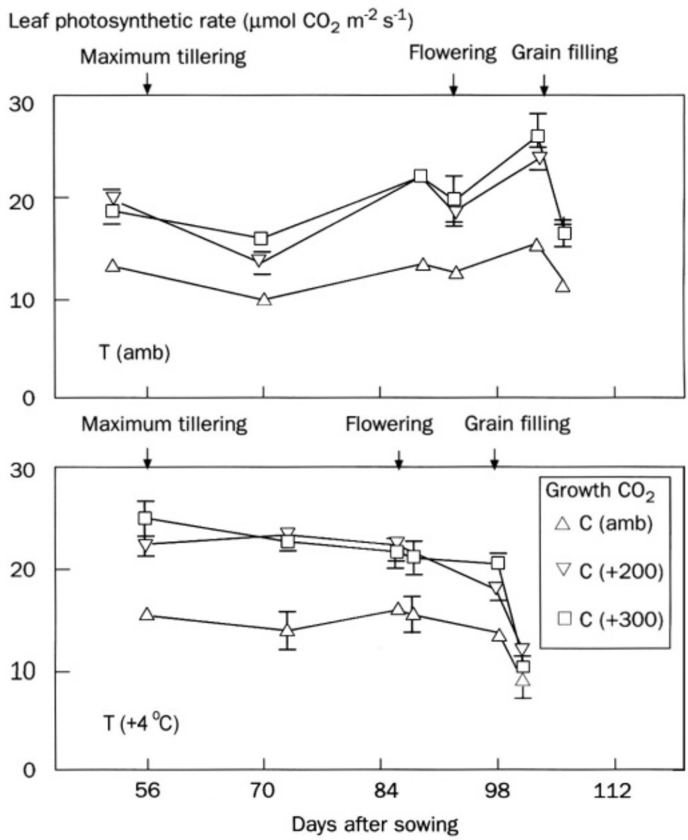



**Fig. 1.** Leaf photosynthetic rates of IR72 grown in open top chambers at the IRRI farm in the 1995 dry season. T (amb) = ambient temperature, T +4 °C = ambient temperature + 4 °C, C (amb) = ambient $CO_2$ concentration, C (+200) = ambient $CO_2$ concentration +200 ppm, C (+300) = ambient $CO_2$ concentration +300 ppm.

less energetically expensive biomass and thus use less $CO_2$ (Bunce 1994). As long as suppression of respiration does not reduce the supply of energy for vital plant functions, it may increase net photosynthesis (Imai 1995). But a $CO_2$-induced modification in respiration rates may result in a lack of energy to repair strained tissues. Also, stomatal aperture may decrease partially because of an inability to maintain the ionic gradients responsible for the opening mechanism of cells (Bunce 1994).

## Biomass accumulation and yield

Aboveground biomass showed distinct patterns for ambient and increased temperatures (Fig. 2). Under the ambient temperature regime at the IRRI farm, the elevated

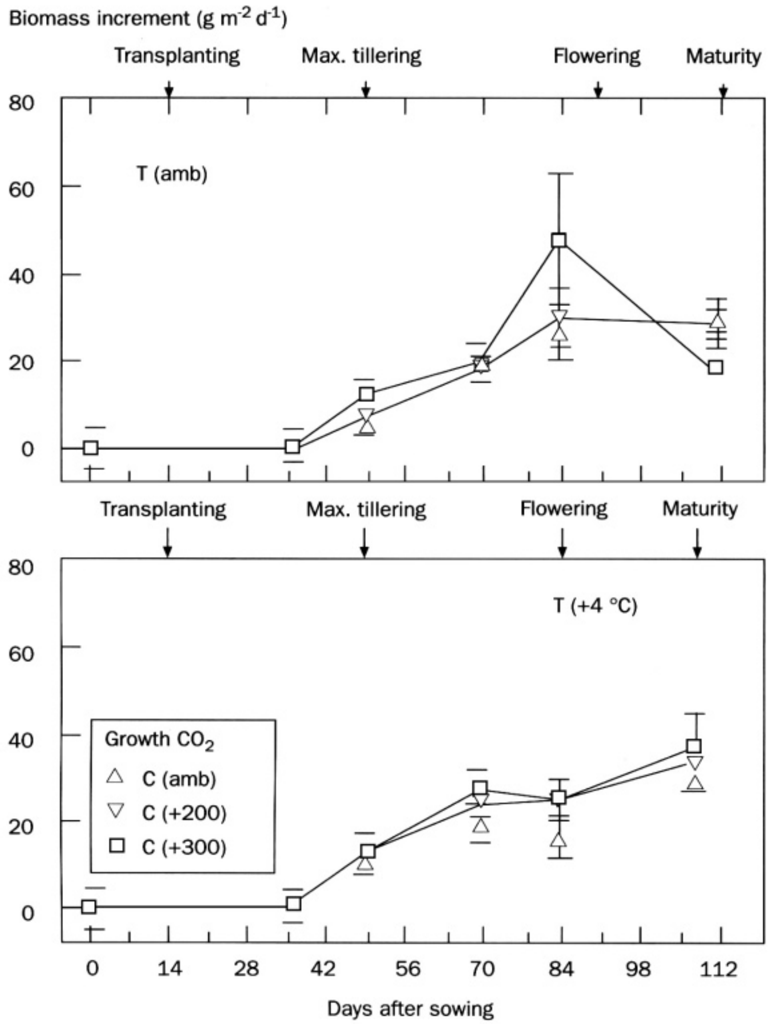



**Fig. 2.** Increment in aboveground biomass (g $m^{-2}$ $d^{-1}$) of IR72 grown in open top chambers at the IRRI farm in the 1995 dry season. T (amb) = ambient temperature, T+4 ºC = ambient temperature +4 ºC, C (amb) = ambient $CO_2$ concentration, C (+200) = ambient $CO_2$ concentration +200 ppm, C (+300) = ambient $CO_2$ concentration +300 ppm.

$CO_2$ levels resulted in a distinct boost during the grain-filling stage. This boost was not observed at higher temperatures when the increments remained in a relatively stable range throughout the reproductive and ripening stages. Table 1 summarizes the agronomic characteristics of the mature plants. Harvested biomass (aboveground plus roots) increased with higher $CO_2$ concentrations, an effect observed for both tempera-

**Table 1. Plant growth properties of IR72 grown in open top chambers at the IRRI farm in the 1995 dry season.**

| Variable | Units | T (amb)[a] | | | T (+4 °C) | | |
|---|---|---|---|---|---|---|---|
| | | C (amb) | C (+200) | C (+300) | C (amb) | C (+200) | C (+300) |
| Green leaf area | ($cm^2$ $hill^{-1}$) | 1,185 b | 1,046 b | 1,103 b | 1,349 ab | 1,561 a | 1,394 ab |
| Leaf weight | ($g\ m^{-2}$) | 285.5 b | 287.3 b | 289.3 b | 301.4 b | 289.3 b | 371.2 a |
| Stem weight | ($g\ m^{-2}$) | 471.0 b | 589.2 ab | 635.3 a | 469.4 b | 643.6 a | 683.6 a |
| Root weight | ($g\ m^{-2}$) | 390.0 b | 501.5 b | 516.5 a | 270.0 c | 423.0 b | 489.1 a |
| Root-shoot ratio | | 0.19 b | 0.23 a | 0.23 a | 0.16 c | 0.19 b | 0.20 b |
| Panicle weight | ($g\ m^{-2}$) | 726 c | 1,076 a | 1,099 a | 671 c | 854 b | 930 ab |
| 1,000-grain weight | (g) | 24.8 a | 24.6 a | 24.9 a | 22.3 b | 23.4 ab | 23.4 ab |
| Filled spikelets | (%) | 84.7 a | 84.8 a | 85.1 a | 82.4 a | 80.5 ab | 77.2 b |
| Harvest index | | 0.47 a | 0.46 a | 0.47 a | 0.39 b | 0.39 b | 0.38 b |

[a] T (amb) = ambient temperature, T (+4 °C) = ambient temperature plus 4 °C. C (amb) = ambient $CO_2$ concentration, C (+200) = ambient $CO_2$ concentration +200 ppm, C (+300) = ambient $CO_2$ concentration +300 ppm. In a row, means followed by the same letter are not significantly different at the 5% level by Duncan's multiple range test.

ture regimes. The impact of the rise in temperature depended on the $CO_2$ level—lower biomass under ambient temperatures and higher biomass under a higher $CO_2$ concentration.

Rice yield increased with increasing atmospheric $CO_2$ at a given temperature regime. The average rice yields at the intermediate and high $CO_2$ were 1 t $ha^{-1}$ higher than for rice grown at ambient $CO_2$ (Fig. 3). The yield increment accrued from increased weight per panicle at an increasing $CO_2$ concentration, whereas the weight of individual grains was fairly stable over the $CO_2$ treatments (Table 1). In sum, irrigated rice production at ambient growth temperature (25 °C) will benefit from increased atmospheric $CO_2$ as such. The increased rates of $CO_2$ assimilation and decreased rates of maintenance (dark) respiration at elevated $CO_2$ resulted in increased plant biomass accumulation. Grain yield also increased with increasing atmospheric $CO_2$ concentration.

## Environmental limitation and management options for exploiting $CO_2$ effects

The actual impact of enhanced $CO_2$ levels on agriculture will depend on the availability of water and nutrients as well as climatic factors. The ultimate linkage between atmospheric $CO_2$ and temperature results in a number of uncertainties about the overall benefit from $CO_2$ "fertilization." Several synergistic pathways of $CO_2$ and temperature were shown above, but temperature also affects plant development independently, for example, through shorter vegetation periods and spikelet sterility. A temperature increase of 4 °C accelerated plant development until maturity by 4 d in our experiment. Shorter cropping periods may allow a shift in planting dates and the introduction of long-maturing varieties at some locations. The potential benefit of

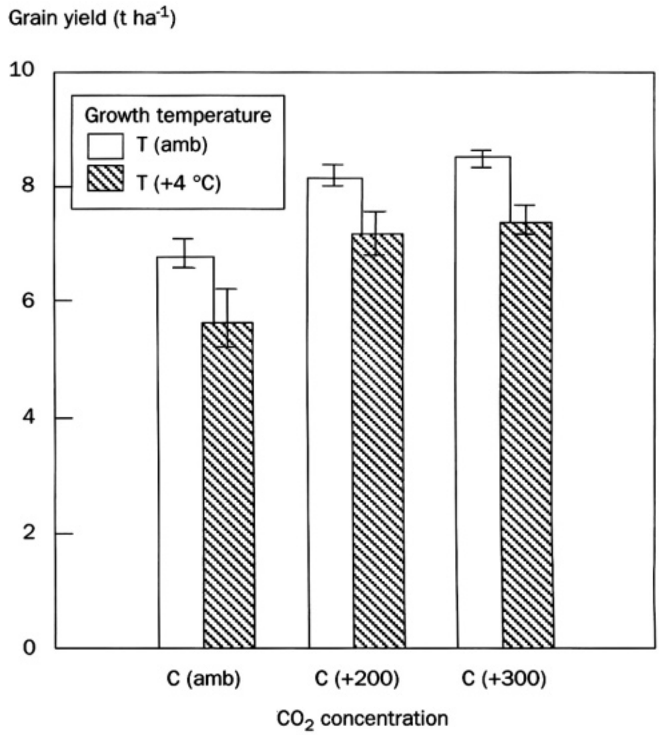



**Fig. 3.** Grain yield at maturity (t $ha^{-1}$) of IR72 grown in open top chambers at the IRRI farm in the 1995 dry season. T (amb) = ambient temperature, T +4 °C = ambient temperature +4 °C, C (amb) = ambient $CO_2$ concentration, C (+200) = ambient $CO_2$ concentration +200 ppm, C (+300) = ambient $CO_2$ concentration +300 ppm.

such modifications, however, may be limited by the sensitivity of rice plants to the actual temperature regime at specific plant stages. High temperatures during flowering may result in abundant spikelet sterility, which was shown to be a decisive mechanism in determining rice yields in a future climate (Matthews et al 1995). A small change in the mean temperature or even an altered temperature pattern could cause pronounced effects on production because of the extreme sensitivity of spikelet fertility to temperature at a very distinct and short period of time.

Crop models coupled to global climate-change scenarios yield different results, depending on the model and the scenario used. Simple crop models usually indicate higher rice production. As an example, Leemans and Solomon (1993) predicted an 11% increase. The more sophisticated IBSNAT model showed a 2–4% reduction in global rice production (Rosenzweig and Parry 1994). These losses are mainly attributed to low latitudes; crop yields in mid- and high latitudes are predicted to increase. Matthews et al (1995) coupled the ORYZA and SIMRIW models to different climate-change scenarios and obtained an overall impact on rice production in Asia ranging from +6.5% to -12.6%. The average of these computations suggests that rice production in Asia may decline by 3.8% (Matthews et al 1995). But the detrimental effects of an increase in temperature may be ameliorated by varietal adaptation. The level of adaptation required (e.g., for spikelet fertility) is within the genotypic variation currently present in environments with hot climates (Matthews et al 1995).

Rice cultivars exhibit a range of adaptation to changing global $CO_2$ and temperature. Although some varieties may be unable to cope with changing $CO_2$ and temperature, others may be able to optimize them for increased vegetative and reproductive growth. Of the 22 species (other than *sativa*) of the genus *Oryza,* commonly called the wild relatives of rice, several possess photosynthetic characteristics equal to and, in some respects, superior to modern cultivars. At increased growth temperature, some varieties may be insensitive to high $CO_2$ levels; others may experience reduced growth and yield. The mechanisms of varieties that exploited high $CO_2$ and temperature for vegetative and reproductive growth must be further investigated.

Enhanced levels of atmospheric $CO_2$ can influence the competitive ability of rice against weeds—namely, those with a $C_4$ metabolism. Plant species that follow the $C_3$ photosynthetic pathway produce a primary compound consisting of 3 carbon atoms, whereas others produce mainly a compound consisting of 4 carbon atoms ($C_4$ pathway). $C_4$ plant species have $CO_2$-concentrating mechanisms that enhance photosynthetic potential at ambient $CO_2$ concentrations. This supplementary mechanism results in a lower response to increasing $CO_2$ levels in the atmosphere compared with $C_3$ plants. Rice, a $C_3$ plant, may sharpen its competitive edge against a $C_4$ weed in the future when atmospheric $CO_2$ rises. IR72 produced more biomass than *Echinochloa crus-galli*— a $C_4$ weed species—at increased $CO_2$ levels in the glasshouse (data not shown).

Photosynthetic rates of IR72 grown at two $CO_2$ levels and three N levels decreased at high $CO_2$ when N was not applied (data not shown). In the future, rice growth and yield responses to increasing $CO_2$ levels may depend on available N. Aboveground biomass and yield increased with increasing $CO_2$ levels even when phosphorus (P) was not applied, but growth and yield benefits will increase further with increasing $CO_2$ when P is applied (Seneweera et al 1994).

Overall, rice ecosystems will absorb more $CO_2$ for the production of biomass, which will also involve an increased turnover of soil organic C. The bulk of the biomass as well as the easily degradable soil organic matter will be released in the form of $CO_2$ after harvest, but a long-term sequestration of C may occur in the enhanced formation of relatively inert organic compounds in the soil. Intensified rice production increased the amount of inert organic material in the soil (Cassmann et al 1995); this process could become more significant in the future with a further increase in productivity by "$CO_2$ fertilization." The quantification of this C sink, which could act as a negative feedback mechanism to an increase in $CO_2$ , is a crucial question in the overall assessment of rice production and global change.

## Possible effects of increased UV-B radiation

One class of atmospheric trace gases, the CFCs, has a twofold effect on the environment. This group of gases contributes—with minor importance—to global warming, but the real threat derives from the catalytic degradation of ozone in the stratosphere (Cicerone 1987). The stratospheric ozone layer filters out much of the short-wave component of the solar spectrum before it penetrates the Earth's surface. Increasing radiation will have severe effects on human health and on terrestrial and marine ecosystems. But the ban implemented on CFCs in industrialized countries is expected to reverse the declining trend of stratospheric ozone concentrations within the coming decades.

Ultraviolet radiation with wavelengths from 280 to 320 nm (termed UV-B) is readily absorbed by biochemical molecules, such as proteins and nucleic acids, resulting in a destruction of chemical bonds (Tevini and Teramura 1989). The natural UV-B radiation in the tropics is considerably stronger than that in the higher latitudes because the ozone layer is thinner in the tropics and the solar angles are higher. The depletion in the ozone layer in these regions with significant rice cultivation corresponds to 1.6–3.1% (NASA 1988). On the other hand, a large portion of the UV-B radiation in the tropics and subtropics is captured by clouds, especially during the monsoon season.

Rice plants are relatively resistant to enhanced UV-B radiation. In field studies, the modern varieties disseminated by IRRI did not show a significant change in growth and yield as a result of enhanced UV-B radiation (Dai et al 1995). A screening of 188 cultivars originating from various locations confirmed that rice plants cope with relatively high UV-B radiation (Dai et al 1994). This resilience appears to be related to the effective mechanisms of DNA repair that are stimulated by other components of the solar spectrum, such as UV-A radiation. These findings led to the conclusion that increased UV-B exposure will not cause significant yield losses in global rice production. The impact of enhanced UV-B in some areas (such as outside the humid tropics) should be considered separately. Furthermore, increased UV-B radiation could have indirect effects on plant competitive interactions, biodiversity of rice cultivation, and pest-pathogen relationships in rice systems.

## Greenhouse gas emissions from rice fields

### Processes involved in methane emissions

Methane is generated in the anaerobic layers of rice soils (Fig. 4). The organic material converted to $CH_4$ is derived mainly from soil organic matter, plant-borne material, and—if applied—organic manure (Neue 1993). Methane is produced in the last step of different biochemical pathways. The decomposition rate of the organic material determines the availability of immediate precursors of methane and, thus, the *in situ* rates of $CH_4$ production. Methane production requires a redox potential of less than -200 mV, which is commonly found in rice soils 2 wk after flooding (NeUE 1993). But the upper micro layer (<1 cm) and parts of the rhizosphere are generally

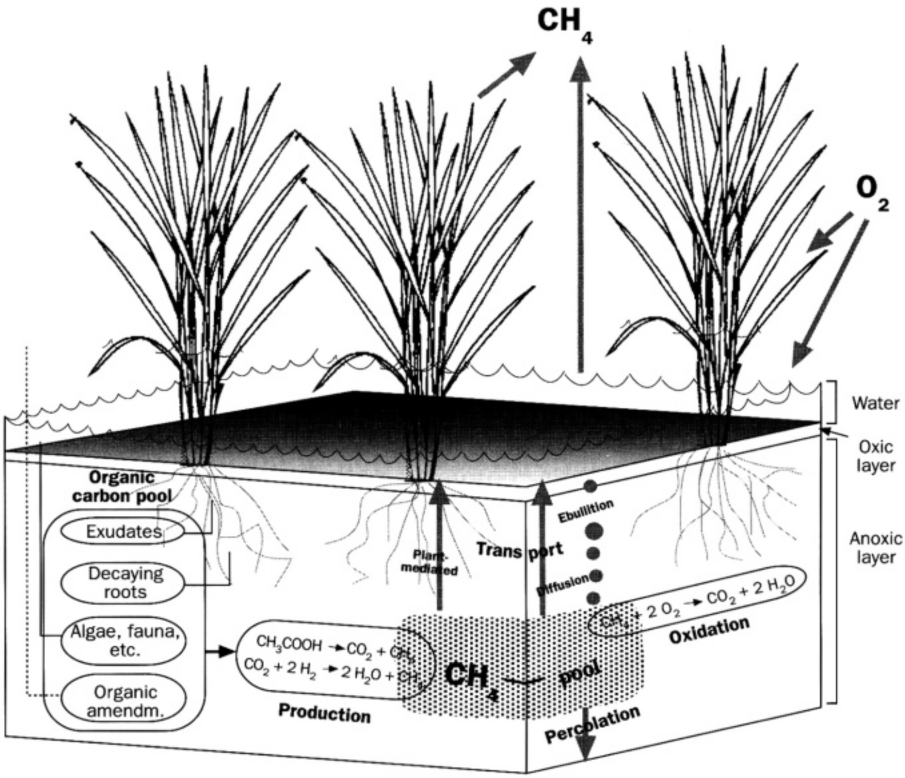



**Fig. 4.** A schematic view of the methane budget in rice fields.

aerobic, thus facilitating microbial $CH_4$ oxidation (Fig. 4). In previous field studies, $CH_4$ production rates exceeded the actual amount of $CH_4$ released from the field by a factor of 2–4 (Holzapfel-Pschorn et al 1985), indicating intensive consumption of $CH_4$. Because methanotrophic bacteria can also oxidize ammonia, $CH_4$ oxidation is closely linked to the N cycle (Conrad and Rothfuss 1991).

The $CH_4$ produced in the flooded rice soil can be transferred to the atmosphere by different pathways (Fig. 4). In the early stage of the cropping period, the efflux of $CH_4$ from rice fields is mainly attributed to the emergence of gas bubbles (Wassmann et al 1996a). Diffusive transport of $CH_4$ through the water column was shown to be minor in rice fields, whereas the transfer of $CH_4$ through the rice plants gradually increases with plant growth and becomes the dominant pathway within the mature plant stages (Wassmann et al 1996a). Percolation can also be a sink for soil-borne $CH_4$, but cultural practices in wetland rice aim to reduce water losses to levels that are negligible for the $CH_4$ methane conveyed.

## Methane emissions in different rice ecosystems

Rice ecosystems are commonly classified into four categories with generic hydrological conditions (IRRI 1993). Irrigated rice comprises approximately 51% of the global rice land (IRRI 1995) and is characterized by full control of the water regime. Because of prevailing anaerobic conditions during continuous flooding, $CH_4$ emission rates from irrigated rice gradually increase during the first half of the growing season and remain high during the ripening stage. But irrigated rice is rarely flooded throughout the entire season without interruptions; intervals with dry soil conditions may significantly lower $CH_4$ emission rates (Wassmann et al 1995).

In the absence of irrigation facilities, rainfed rice (27% of the global rice land) is especially prone to fluctuations in the water regime, depending on local precipitation and topography. Methane emissions from rainfed rice will increase with projected improvements in the water supply of this ecosystem. Long submergence and growing periods usually favor $CH_4$ emission rates in the third category, deepwater rice (10% of global rice land). A large proportion of deepwater rice, however, is found in coastal areas where $CH_4$ generation is inhibited by saline conditions. The fourth rice ecosystem, upland rice (11% of global rice land), is not associated with flooding and can therefore be neglected in terms of $CH_4$ source.

Irrigated rice is clearly the most important rice ecosystem for $CH_4$ emissions in the global context because it has the highest annual emissions per harvested area and is the most extensive (Wassmann et al 1995). Therefore, the following discussion on influencing factors and mitigation strategies focuses on this rice ecosystem. Table 2 shows the effects of various factors on $CH_4$ emissions from irrigated rice fields. These observations were obtained by standardized and automated measurements at the IRRI research farm in the Philippines and in collaboration with national agricultural systems at seven sites in five major rice-growing countries in Asia (Wassmann et al 1995).

## Natural factors influencing methane emissions

The magnitude and pattern of $CH_4$ emissions have been shown to be variously affected by soils and climates. Methane production, a biological process, depends on the soil organic C content and quality, texture, Eh/pH buffer capacity, Fe content, sulfate content, and salinity (Neue and Roger 1994). Methane production is optimum in flooded rice fields under these conditions: a redox potential below -200 mV, a narrow range of pH between 6 and 8, and a temperature above 10 °C. But soil properties also affect $CH_4$ oxidation and transfer to the atmosphere, resulting in a complex web of interrelations among factors and processes.

A laboratory incubation study of rice-growing soils from the Philippines resulted in a classification scheme for soils according to $CH_4$ production potential (Wassmann et al, submitted). The potential of soils is composed of two traits: the inherent production capacity and the response profile of soil organic amendments. The inherent capacity for methane production was correlated to the enriched fraction of soil organic material. This fraction is defined as the differential between topsoil and subsoil

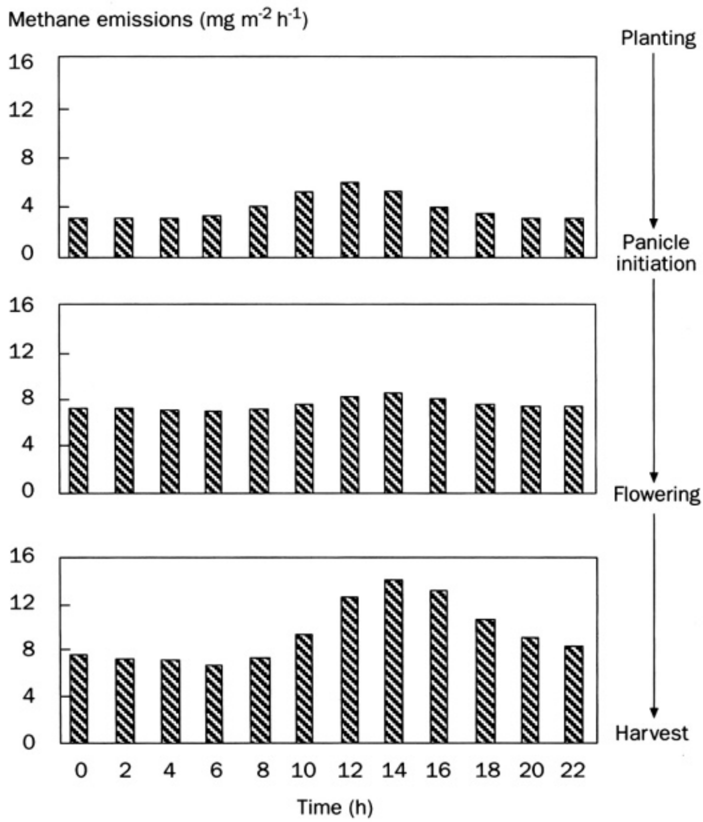



**Fig. 5.** Diel pattern of methane emission rates from irrigated rice fields in Thailand (Prachinburi), Indonesia (Jakenan), and the Philippines (Los Baños and Maligaya) compiled as a summary of all available records for respective plant stages.

concentrations of soil organic matter and comprises readily decomposable material. The most indicative parameters for the response profile in different soils were pH value and organic carbon content when combined in a multivariate regression (Wassman et al 1998).

Methane fluxes are modulated by diel patterns of temperature and are thus relatively uniform across sites in similar climates (Buendia et al 1998). The amplitude depends on plant stage; $CH_4$ emission rates during the early and late stage fluctuate, with a distinct maximum in the early afternoon, whereas this pattern is less pronounced in the middle stage (Fig. 5). The seasonal patterns in field experiments without organic manure generally correspond to a gradual increase in emission rates until the ripening stage of the plant.

**Table 2. Influencing components in irrigated rice and their significance for methane emission rates (* = weak, ** = moderate, *** = high) as well as impact mechanisms and their effects (↑↓= weak, ⇧⇩ = moderate, ⬆⬇= high stimulation or inhibition, respectively).**

| Influencing component | Significance | Impact mechanism | Effect |
|---|---|---|---|
| Soil | ** | Indigenous methanogenic material | ⇧ |
| | | Chemical inhibition of methane production | ⇩ |
| | | Texture with high porosity | ↑ |
| Climate | * | High and evenly distributed precipitation | ⇧ |
| | | Low temperature | ↓ |
| | | Hazardous events | ↓ |
| Water management | *** | Long duration of flooding | ⬆ |
| | | Continuous flooding in early season | ⬆ |
| | | Continuous flooding in late season | ↑ |
| | | Strong leaching | ↓ |
| Organic amendments | *** | Removal of plant residues | ⇩ |
| | | High doses of manure | ⬆ |
| | | Replacement of fresh manure by biogas residues | ⇩ |
| | | High organic inputs from floodwater | ↑ |
| Nutrient and crop management | * | Use of sulfate fertilizers | ↓ |
| | | High N inputs | ↑ |
| | | Dense spacing of rice plants | ↑ |
| | | Frequent soil disturbance | ↑ |
| Rice cultivar | ** | Strong root exudation | ⇧ |
| | | High oxidation power | ↓ |
| | | High diffusion resistance for methane transport | ⇩ |
| | | Short cropping period | ↓ |

## Agricultural practices

Water management and fertilizer application decisively influence the magnitude of greenhouse gas emissions (Wassmann et al 1993a). These two components were observed to have the most pronounced effect on $CH_4$ emissions in irrigated rice fields (Table 2). Various aspects of the effects of the water regime on greenhouse gas emissions were already mentioned in the context of the hydrological conditions inherent in the different rice ecosystems. Continuous flooding favors $CH_4$ emissions, whereas temporary dry conditions suppress their generation. Distinct aeration periods may occur as part of a management practice such as pesticide application or as a result of insufficient water supply caused by drought. Dry periods within the first half of the season impede $CH_4$ production and enhance $CH_4$ oxidation, resulting in low $CH_4$ emission rates even after the field is flooded again (Fig. 6).

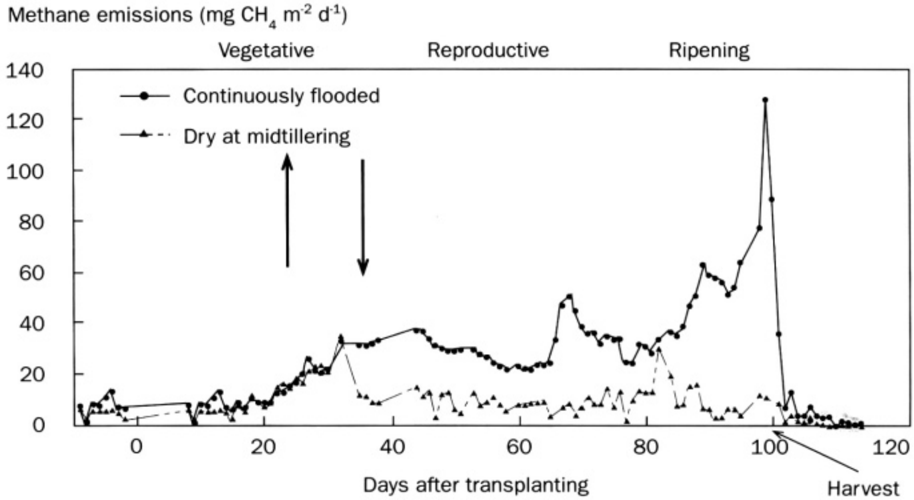



**Fig. 6.** Methane emission rates in the 1994 wet season at Los Baños (Philippines); upward and downward arrows represent outgoing and incoming water, respectively, for the treatment with drying at midtillering.

Incorporating organic material usually enhances $CH_4$ emission rates because of the availability of substrates for methanogenesis from the organic inputs. The effect of organic fertilizers is limited to the first half of the cropping period, whereas the emission rates during the second half are relatively uniform in a given rice field regardless of fertilizer treatment (Fig. 7A,B). Because of the dominance of ebullition in the early stage, the increment in $CH_4$ emissions triggered by organic amendments is caused mainly by the emergence of gas bubbles (Fig. 7A,B). The increasing application of mineral fertilizers and the concomitant decline in organic amendments have a reducing effect on $CH_4$ release from rice land as long as the other parameters, such as water regime, remain constant.

Soil disturbances such as land preparation, postharvest drying, and weeding release pulses of soil-entrapped $CH_4$. Adding urea fertilizer generally enhances $CH_4$ emissions, whereas sulfate-containing fertilizers depress emissions. The traits of rice cultivars also influence methane emissions. Root exudates are a major source of methanogenic substrate and the aerenchyma of the plant acts as a conduit for $CH_4$ and $O_2$. In laboratory experiments with three different cultivars, the high-yielding variety was associated with the lowest root exudation; in field experiments, this variety showed the lowest methane emissions (Neue et al 1996).

## Interaction of methane and nitrous oxide emissions

Nitrous oxide is generated in rice soils by two microbial processes—denitrification and nitrification (Rennenberg et al 1992). Denitrification is an anaerobic process and

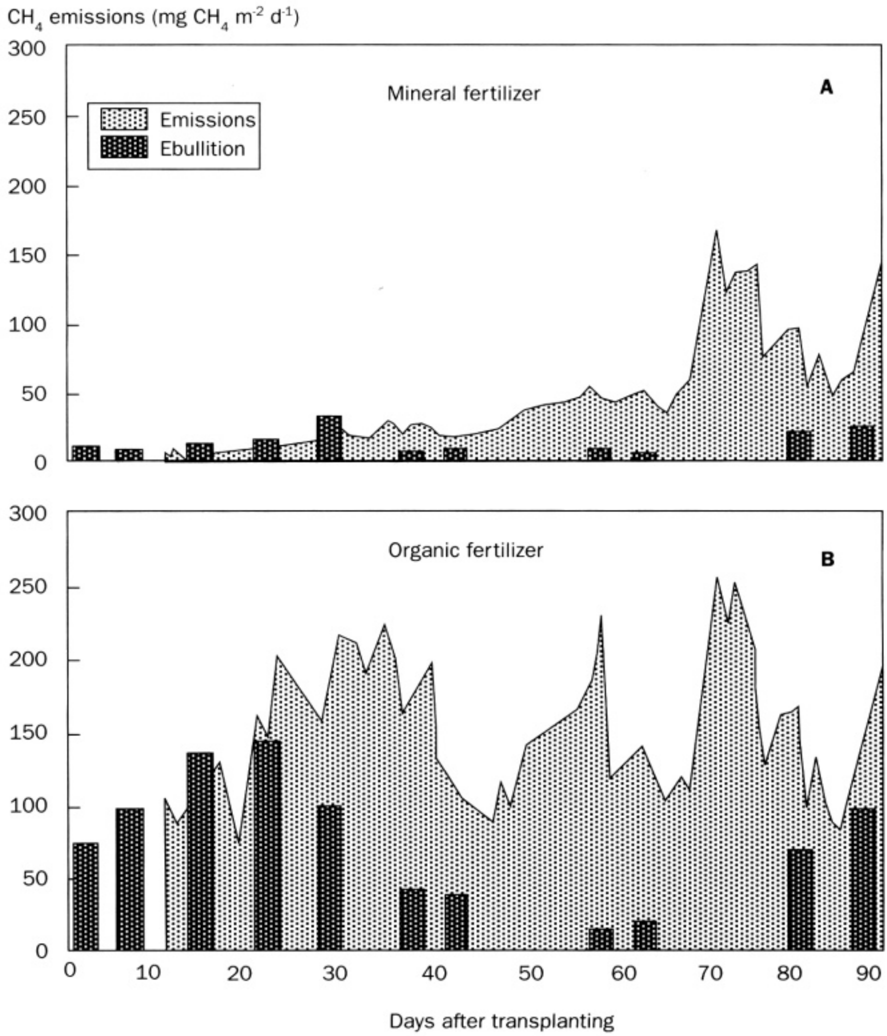



**Fig. 7.** Methane ebullition and emission rates in the 1992 wet season at Los Baños (Philippines) with urea (A) and rice straw (B) treatments.

nitrification is aerobic. Denitrification is the last step in the N cycle, in which oxidized N is converted to molecular form. Nitrification comprises several biochemical pathways in which ammonium is oxidized into nitrate. The intensity of these two processes in wetland rice fields depends strongly on the available N and moisture regime in the soil (Bronson and Singh 1995). Farmers usually avoid applying nitrate to wetland rice because of N losses in denitrification. Drying of the soil stimulates nitrification and also causes losses of N. In both cases, N escapes from the soil in the form of $N_2O$ emissions.

The pattern of $N_2O$ fluxes shows a pronounced antagonism to $CH_4$ fluxes (Bronson et al 1996). Long periods of flooding facilitate high $CH_4$ emissions, whereas microbial N conversion and thus $N_2O$ emissions are low. The N turnover and $N_2O$ emissions are accelerated by dry periods, which reduce $CH_4$ emissions.

## Source strength and mitigation options

Data available on methane emissions increased in recent years through various efforts to improve regional and global estimates on emissions of the greenhouse gas $CH_4$. Rice fields were identified as one of the main sources of $CH_4$, but the global source strength can only be estimated in a broad range from 20 to 100 $10^{12}$ g $CH_4$ yr $^{1}$ , which corresponds to 4–20% of the global $CH_4$ emissions, respectively (GEIA 1993). One of the main reasons for these uncertainties is that methane emission is the complex interaction of natural and anthropogenic factors in regulating $CH_4$ emission rates (Bachelet and Neue 1993). Given the spatial heterogeneity of $CH_4$ emissions and the pronounced temporal variations, surveys of $CH_4$ emissions from rice growing require sound experimental designs and procedures for extrapolations. Furthermore, a great deal of divergence between different estimates of $CH_4$ source strengths can be attributed to varying methodologies with different sampling frequencies as well as inconsistent definitions of rice ecologies (Neue and Boonjawat 1998).

As with estimates of methane emissions, similar constraints beset the assessment of $N_2O$ emissions from rice cultivation. Nitrous oxide is mainly released in spikes lasting only for a few days, which makes detection of the spikes even more complex. Methane *and* $N_2O$ emissions must be regarded as complementary in exploring possible mitigation options for greenhouse gases from rice fields. Many of the findings on the effects of agricultural practices on $CH_4$ and $N_2O$ emissions can, in turn, be considered mitigation options. The drastic reduction in $CH_4$ emissions by temporary drying of the field did not affect yield. Midseason drying is widely recommended to impede the formation of unproductive tillers and could therefore become a commonly accepted tool to reduce $CH_4$ emissions in fields with good irrigation facilities.

Replacing organic manure with mineral fertilizer decreases $CH_4$ production in the soil and reduces the amount of $CH_4$ emitted. The intensified use of minerals as a mitigation option has to be examined in the context of sustainability of soil fertility as well as increased emissions of $CO_2$ involved in fertilizer production. Large areas planted to rice, such as in China, rely on organic manure because of limited financial resources and limited availability of mineral fertilizers. Therefore, mitigation options should focus on management rather than on replacement of organic amendments in rice cultivation. One strategy—fermentation of organic manure in biogas generators before incorporation into the soil—was shown to reduce $CH_4$ emissions by approximately 30% with given quantities of organic amendments (Wassmann et al 1993b). This strategy is also in line with the overall objective of reducing fossil fuel consumption because the $CH_4$ generated is used directly in farmers' households as cooking gas. Assuming a given amount of manure, feasible strategies of reducing emissions could also be developed by considering the spatial and seasonal distribution of fertilizers (Wassmann et al 1996b).

Researchers are now exploring the potential of selecting rice cultivars for mitigating $CH_4$ emissions. Reduced exudation from rice roots would combine a lower availability of methanogenic substrate along with higher assimilate efficiency for the plants. The diversity of rice cultivation, however, requires an integrated strategy that has to be optimized under site-specific conditions. The reduction of $CH_4$ and $N_2O$ represents losses of energy and nutrients for the system. Developing strategies to reduce greenhouse gas emissions through cultivar selection as well as other measures can therefore be seen as one component of advanced resource management.

## Challenges for future research

The research on global change and rice carried out by IRRI and other institutions yielded an ample array of information on individual aspects of the prospects for production under changing climate as well as the contribution by rice fields to global warming. But the real challenge is to combine segregated information into an integrated assessment of the interactions of global climate and rice production. The following topics should highlight some areas of specific interest that still have to be addressed by future research:

- Possible feedback processes of climate change and rice through altered emissions of greenhouse gases.
- The impact of intensified rice production on the hydrological cycle and the global cycles of C and N.
- The link between global climate change and biodiversity of the rice gene pool.
- The adaptation potential of rice cultivation in coastal areas affected by a rise in sea level.

The overwhelming significance of rice for feeding the people of Asia and other continents requires a thorough assessment of both the prospects and impact of rice cultivation in a changing world.

## References

Bachelet D, Neue HU. 1993. Methane emissions from wetland rice area of Asia. Chemosphere 26(1-4):2 19-237.

Baker JT, Laugel F, Boote KJ, Allen LH Jr. 1992. Effects of daytime carbon dioxide concentration on dark respiration in rice. Plant Cell Environ. 15:231-239.

Bronson KF, Singh U. 1995. Nitrous oxide emissions from flooded rice. In: Peng S, Ingram K, Neue HU, Ziska LH, editors. Climate change and rice. Berlin: Springer-Verlag. p 116-121.

Bronson KF, Neue HU, Singh U, Abao E. 1996. Automated chamber measurement of $CH_4$ and $N_2O$ flux in a flooded rice soil. I. Effect of residue, nitrogen, and water management. Soil Sci. Soc. Am. 61:981-987.

Bronson KF, Cassman KG, Wassmann R, Olk DC, van Noordwijk M, Garrity D. 1998. Soil carbon dynamics in different cropping systems in principal ecoregions of Asia. In: Lal R, Kimble JM, Follett RF, Stewart BA, editors. Management of carbon sequestration in soil. Boca Raton, Fla. (USA): CRC Press. p 35-57.

Buendia L, Neue HU, Wassmann R, Lantin RS, Alberto MCR, Aduna JB, Javellana AM, Arah J. 1998. An efficient sampling strategy for estimating methane emissions from rice. Chemosphere 36:395-407.

Bunce JA. 1994. Responses of respiration to increasing atmospheric carbon dioxide. Physiol. Plant. 90:427-430.

Cassman KG, De Datta SK, Olk DC, Alcantara JM, Samson MI, Descalsota JP, Dizon MA. 1995. Yield decline and the nitrogen economy of long-term experiments on continuous, irrigated rice systems in the tropics. In: Lal R, Stewart BA, editors. Soil management: experimental basis for sustainability and environmental quality. Boca Raton, Fla. (USA): Lewis/CRC Publishers.

Cicerone RJ. 1987. Changes in stratospheric ozone. Science 237:35-42.

Conrad R, Rothfuss F. 1991. Methane oxidation in the soil surface layer of a flooded rice field and the effect of ammonium. Biol. Fert. Soils 12:28-32.

Dai Q, Peng S, Chavez AQ, Vergara BS. 1994. Intra-specific responses of 188 rice cultivars to enhanced UV-B radiation. J. Environ. Exp. Bot. 34:433-442.

Dai Q, Peng S, Chavez AQ, Vergara BS. 1995. Effect of enhanced UV-B radiation on growth and production of rice under greenhouse and field conditions. In: Peng S, Ingram KT, Neue HU, Ziska LH, editors. Climate change and rice. Berlin: Springer Verlag. p 189-198.

GEIA (Global Emission Inventory Activity). 1993. Report on the 3rd workshop, 31 Jan-2 Feb 1993, Amersford. Bowman AF, editor. The Netherlands: Bilthoven. 83 p.

Holzapfel-Pschorn A, Conrad R, Seiler W. 1985. Production, oxidation, and emission of methane in rice paddies. FEMS Microbiol. Ecol. 31:149-158.

Imai K. 1995. Physiological response of rice to carbon dioxide, temperature and nutrients. In: Peng S, Ingram KT, Neue HU, Ziska LH, editors. Climate change and rice. Manila (Philippines): International Rice Research Institute, and Germany: Springer Verlag.

IPCC (Intergovernmental Panel on Climate Change). 1990. Climate change. The IPCC scientific assessment. Cambridge University Press. XXXIX + 358 p.

IPCC (Intergovernmental Panel on Climate Change). 1992. Climate change. The supplementary report to the IPCC scientific assessment. Cambridge University Press. 200 p.

IRRI (International Rice Research Institute). 1993. IRRI rice almanac. Manila (Philippines): IRRI. 142 p.

IRRI (International Rice Research Institute). 1995. World rice statistics 1993-1995. Manila (Philippines): IRRI.

Kropff MJ, Matthews RB, van Laar HH, ten Berge HFM. 1995. The rice model ORYZA1 and its testing. In: Matthews RB, Kropff MJ, Bachelet D, van Laar HH, editors. Modeling the impact of climate change on rice production in Asia. Wallingford (UK): CAB International, and Manila (Philippines): International Rice Research Institute. p 27-50.

Leemans R, Solomon AM. 1993. Modeling the potential yield and distribution of earth's crops under a warmed climate. Clim. Res. 3:79-96

Matthews RB, Kropff MJ, Bachelet D, van Laar HH. 1995. Modeling the impact of climate change on rice production in Asia. Wallingford (UK): CAB International. 289 p.
NASA (National Aeronautical and Space Administration). 1988. Present state of knowledge of the upper atmosphere 1988: an assessment report by the Ozone Trend Panel. NASA reference publication 1208. Washington, D.C. (USA): NASA Office of Space Studies and Application.
Neue HU. 1993. Methane emission from rice fields. Bioscience 43:466-474.
Neue HU, Roger PA. 1994. Potential of methane emission in major rice ecologies. In: Zepp RG, editor. Climate-biosphere interactions. New York (USA): Wiley. p 65-93.
Neue HU, Boonjawat J. 1998. Methane emission from ricefields. In: Galloway J, Melillo J, editors. Asian change in the context of global change. IGBP Book Series. Cambridge University Press. (In press.)
Neue HU, Ziska LH, Matthews RB, Dai Quije. 1995. Reducing global warming: the role of rice. GeoJournal 35(3):351-362.
Neue HU, Wassmann R, Lantin RS, Alberto MCR, Aduna JB, Javellana AM. 1996. Factors affecting methane emission from rice fields. Atm. Environ. 30:1751-1754.
Rennenberg H, Wassmann R, Papen H, Seiler W. 1992. Trace gas exchange in rice cultivation. Ecol. Bull. 42:164-173.
Rosenzweig C, Parry ML. 1994. Potential impact of climate change on world food supply. Nature 367:133-138.
Seneweera S, Milham P, Conroy J. 1994. Influence of elevated $CO_2$ and phosphorus nutrition on the growth and yield of a short-duration rice (*Oryza sativa* L. cv Jarrah). Aust. J. Plant Physiol. 21(3):281-292.
Tevini M, Teramura AH. 1989. UV-B effects on terrestrial plants. Photochem. Photobiol. 50:479-487.
Wassmann R, Papen H, Rennenberg H. 1993a. Methane emission from rice paddies and possible mitigation options. Chemosphere 26:201-217.
Wassmann R, Wang MX, Shangguan XJ, Xie XL, Shen RX, Papen H, Rennenberg H, Seiler W. 1993b. First records of a field experiment on fertilizer effects on methane emission from rice fields in Hunan Province (PR China). Geophys. Res. Lett. 20:2071-2074.
Wassmann R, Neue HU, Lantin RS, Javellana MJ, Diego R, Lignes VE, Hoffmann H, Papen H, Rennenberg H. 1995. Methane emissions from rainfed rice. In: Fragile lives in fragile ecosystems. Manila (Philippines): International Rice Research Institute. p 217-225.
Wassmann R, Neue HU, Alberto MCR, Lantin RS, Bueno C, Llenaaresas D, Arah JRM, Papen H, Seiler W, Rennenberg H. 1996a. Fluxes and pools of methane in wetland rice soils with varying organic inputs. Environ. Monitoring Assess. 42:163-173.
Wassmann R, Shangguan XJ, Tölg M, Cheng DX, Wang MX, Papen H, Rennenberg H, Seiler W. 1996b. Spatial and seasonal distribution of organic amendments affecting methane emission from Chinese rice fields. Biol. Fert. Soils 22:191-195.
Wassmann R, Neue HU, Bueno C, Lantin RS, Alberto MCR, Buendia LV, Bronson K, Papen H, Seiler W, Rennenberg H. 1998. Methane production potentials of different rice soils derived from intrinsic and exogenous substrates. Plant Soil, submitted for publication.
Ziska LH, Bunce JA. 1993. Inhibition of whole plant respiration by elevated $CO_2$ as modified by growth temperature. Physiol. Plant. 87:459-466.

## Notes

*Authors' address:* International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines. r.wassman@cgnet.com toti@start.or.th r.lantin@cgnet.com

*Acknowledgments:* The results were obtained through projects supported by the United States Environmental Protection Agency and the United Nations Development Programme/Global Environmental Facility.

*Citation:* Dowling NG, Greenfield SM, Fischer KS, editors. 1998. Sustainability of rice in the global food system. Davis, Calif. (USA): Pacific Basin Study Center, and Manila (Philippines): International Rice Research Institute.

CHAPTER 14

# New Frontier Projects: beyond the pipeline

J. Bennett, J.K. Ladha, V. Schmit, and J. Sheehy

Because of the advent of biotechnology tools over the past 15 years, rice breeding in the 21st century will be able to use many of the discoveries in the basic biosciences to solve problems that have proved intractable using traditional breeding methods. Breeders will also be able to contemplate the introduction of traits that were previously not considered feasible for rice, although they were well known in other crops, such as $N_2$ fixation, apomixis, and perenniality. This chapter describes the rationale for introducing these traits into rice and potential or actual research approaches for achieving these ambitious goals. The chapter concludes with an overview of the challenge of achieving higher yields in rice from the perspective of systems analysis and mathematical modeling. Based on this perspective, New Frontier Projects at IRRI combine the high risk of failure with a high impact if successful. Each project is being evaluated by IRRI and collaborating institutes. These projects extend beyond the pipeline that carries completed research from the laboratory or the breeding plot into farmers' fields.

IRRI is conducting more advanced (upstream) research than ever before. This new emphasis has been endorsed by IRRI's stakeholders, including donors, advanced collaborators, and, most importantly, the national agricultural research systems (NARS) of Asia. The change is a recognition of four important trends: (1) the growing strength of NARS in applied research, (2) the increasing relevance of basic research to international agriculture, (3) the development of new tools that facilitate the application of basic discoveries to agricultural problems, and (4) the emergence of consortia and networks to create partnerships that think globally but act locally. IRRI's role in this emerging scenario is twofold: (1) to adapt basic discoveries to the needs of NARS and of IRRI's own programs and to evaluate them relative to alternative approaches, and (2) to forge partnerships with advanced laboratories that are willing to conduct additional basic research needed to meet important agricultural challenges identified by NARS.

IRRI uses the term New Frontier Project to signify a certain type of upstream research. This research is scientifically risky because it enters uncharted territory, but is likely to have an enormous impact if successful. IRRI is learning how to recognize such a project, when to start it, and how to build a team of partner institutes to provide the necessary critical mass of expertise. This research may take 10–15 years to enter the pipeline that carries IRRI's more downstream products and recommendations from the laboratory to NARS and eventually into farmers' fields.

This chapter discusses three New Frontier Projects. They address important issues: decreasing our dependency on nonrenewable sources of nitrogen, making the benefits of hybrid rice more widely available, and protecting the uplands from erosion. For each project, alternative strategies are presented and preliminary results reported. The chapter also takes a look at some possible future New Frontier Projects: from the perspective of modeling, we look at the barriers to increasing yield and develop a step-by-step approach to recognizing and removing those barriers through research.

## Opportunties for developing nitrogen fixation in rice

Nitrogen supply is critical for achieving yield potential. Rice needs 1 kg of N to produce 15–20 kg of grain. Lowland rice in the tropics can use enough naturally available N to yield 2–3 t $ha^{-1}$. To obtain higher yield, additional N must be supplied. In the next 30 yr, we must produce 70% more rice than the 460 million t of today; much of that increase will have to come from the irrigated rice system. At current levels of N use efficiency, we will require at least double the 10 million t of N fertilizer that are currently used each year for rice production. Manufacturing fertilizer for today's needs requires fossil fuel energy equal to about 15 million t of oil—a nonrenewable resource whose oxidized products threaten human health and the environment.

Rice crops suffer from a mismatch between their N demand and the N supplied as fertilizer. This mismatch results in a 50–70% loss of applied N fertilizer. We can prevent this loss through two basic approaches. One is to regulate the time of N application based on the plant's need to partially increase N efficiency. The other is to increase the ability of the rice system to fix its own N. This latter approach is a long-term strategy with large public and environmental benefits, particularly in helping resource-poor farmers. If half of the N fertilizer applied to the 120 million ha of lowland rice could be obtained from biologically fixed N, the equivalent of about 7.6 million t of oil would be conserved annually.

Recent advances in understanding symbiotic *Rhizobium*-legume interactions at the molecular level and the ability to introduce new genes into rice by transformation have created a new frontier for investigating the possibility of $N_2$ fixation in rice. In 1992, IRRI organized a think-tank workshop to look at the possibility of achieving symbiotic associations/nodulation and $N_2$ fixation in rice (Khush and Bennett 1992). Experts reaffirmed that such opportunities did exist for cereals and recommended that rice be used as a model system. Subsequently, IRRI developed a New Frontier Project to coordinate worldwide collaborative efforts among research centers committed to reducing dependency of rice on mineral N resources. An international Biological Nitrogen Fixation (BNF) working group was established to review research, share research results and materials, and catalyze research (Ladha et al 1997). Four

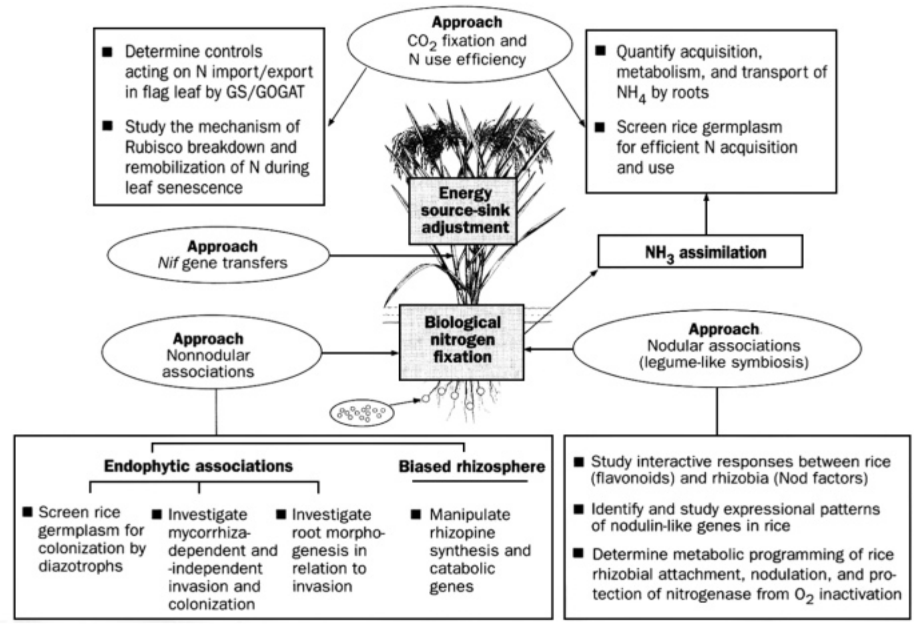



**Fig. 1.** Four potential research approaches for achieving $N_2$ fixation in rice.

approaches to achieving the goal of enabling rice to fix N were identified (Fig. 1). One of these approaches focuses on $CO_2$ fixation and N use efficiency and will not be discussed further here. The remaining three approaches are summarized below.

## Nonnodular associations: development of rice-endophytic diazotroph associations

Diazotrophs such as *Acetobacter diazotrophicus* and *Herbaspirillum* spp. grow endophytically in the stems and leaves of sugarcane. Evidence suggests that *A. diazotrophicus* is the main contributor to endophytic biological $N_2$ fixation (BNF). which, according to N balance studies, was found to be as high as 150 kg N $ha^{-1}$ $yr^{-1}$ in this crop (Boddey et al 1995). Another $N_2$-fixing endophyte of considerable interest is *Azoarcus.* This diazotroph inhabits the roots of Kallar grass (*Leptochloa fusca*), which yields 20–40 t $ha^{-1}$ $yr^{-1}$ of hay without the addition of any N fertilizer in saline-sodic, alkaline soils having low fertility (Sandhu et al 1981). Inoculation experiments with *Herbaspirillum* spp. in nonsterilized soils under greenhouse conditions have shown that these endophytic diazotrophs can be readily introduced into the rice plant by applying bacterial cultures on seeds prior to germination (Olivares et al 1993). Infections occur through roots as well as stomata, and diazotrophs are translocated through the xylem to all parts of the plant. Rice seedlings inoculated with *Herbaspirillurn* spp.

showed $^{15}N$ dilution amounting to a 40% increase in total plant N (Dobereiner et al 1994).

These investigations suggest that endophytic diazotrophs have a considerable potential to contribute to the productivity of nonlegumes, including rice. Our recent studies show that rice plants harbor a wide spectrum of endophytic diazotrophs in root and shoot systems as well as in seeds, and exhibit, to some degree, varietal discrimination in forming associations with the endophytes (Barraquio et al 1997, Stoltzfus et al 1997).

## Nodular associations: development of rice-rhizobia symbiosis

Currently, there is much interest in determining whether rhizobia would be able to nodulate monocots such as rice, and carry out $N_2$ fixation. The possibility of extending the host range of rhizobia to nonlegumes was encouraged by the discoveries that *Parasponia* forms nodules with *Rhizobium* (Trinick 1973) and that *Rhizobium parasponium* RP501 and *Bradyrhizobium* CP283 induce nodulation in oilseed rape (Cocking et al 1990, 1992). Soil bacteria of the genera *Rhizobium, Bradyrhizobium,* and *Azorhizobium* (collectively referred to as rhizobia) interact with leguminous plants to form $N_2$-fixing nodules through a process that begins with secretions of flavonoids from roots, and consequent flavonoid-triggered *nod* gene expression in a microsymbiont, leading to the production of Nod factors. Nod factors induce root hair deformation and promote the processes involved in the initiation of an infection thread and cortical cell division during the early steps of nodulation in legumes (Ardourel et al 1994).

*Rhizobial entry into rice.* In most legumes, rhizobia employ a sophisticated mechanism to enter through root hairs, but rhizobia invading *Parasponia* and certain aquatic legumes, such as *Sesbania* and *Neptunia,* adopt a less specialized mode of entry through the epidermis or cracks created at the sites of the emerging lateral roots. Studies of interactions between rhizobia and rice roots so far have not revealed any invasion through root hairs. Recently, however, several rhizobial strains from *Sesbania* and *Aeschynomene* were found to have the ability to invade emerging lateral roots through a primitive "crack-entry" pathway and induce the formation of short, thick lateral roots (STLRs) in rice (Reddy et al 1997) and wheat seedlings (Cocking et al 1993).

Histochemical analysis of rice seedlings inoculated with *Azorhizobium caulinodans* ORS571 carrying the *nifH::*GUS translocational fusion gene revealed a strong GUS expression in intercellular spaces in subepidermal and cortical cell zones of the roots. Transmission electron microscopy confirmed intercellular azorhizobia colonizing the subepidermal and cortical cell layers of root tissue of rice. Investigations with wild-type and *nod*-mutant strains of *A. caulinodans* ORS571 showed that the ORS571 *nodA*$^-$ not only could invade and colonize rice roots but could also induce STLRs with the same efficiency as that of wild-type strains. These results suggest that, unlike in legumes, Nod factors are not essential for rhizobial infection in rice and that infection through a primitive "crack-entry" mode may facilitate bypassing the cellular machinery needed for the sophisticated type of infection through root hairs (Reddy et al 1997, Webster et al 1997).

*Nodulin genes in rice.* Several genes that affect nodulation and $N_2$-fixation processes in legumes have been identified (LaRue and Weeden 1994). Whereas early nodulin genes (*ENOD*) accomplish crucial processes involved in infection and initiation of nodule development (Mylona et al 1995), late nodulin genes orchestrate the function of the mature nodule (Vance 1990). Several *ENOD* genes are specifically expressed during the initial stages of nodulation, and Nod factors produced by rhizobia have been shown to mediate transcriptional activation of some of these genes. Though the genes similar to many of the late nodulin genes are reasonably widespread in cereals such as rice, not much is known about the presence of the homologs of *ENOD* genes. It is encouraging, however, that Reddy et al (1996) identified and studied the expression of two homologs of *GmN93* (an early nodulin gene of soybean) in *Oryza sativa* var. Nipponbare. Sequencing of cDNA clones of these homologs, *OsENOD93Ha* and *OsENOD93Hb,* has shown that they have sequence homologies within their open reading frames of about 60% to *GmN93.* Both of these genes are primarily expressed in rice roots.

*Nod factors and rice.* Although reports indicate that Nod factors can elicit mitosis and developmental responses in nonlegume dicots, such as carrot and tobacco (de Jong et al 1993, Yang et al 1994), we did not find any perceptible changes in root hair morphology in several rice varieties treated with Nod factors. Recently, however, we found that in the transgenic calli carrying the *MtENOD*12-GUS fusion gene, GUS expression was enhanced when the calli were supplied with Nod factors (Reddy et al 1998). These results clearly suggest that rice has the ability to interact with rhizobia or their Nod factors, and that it possesses some of the gene functions necessary for nodule formation.

## Transferring the *Nif* gene to rice

The approach described here involves transferring the $N_2$-fixation (*nif*) genes into the rice genome. These genes include *nifH, nifD,* and *nifK* to encode the three structural polypeptides of nitrogenase. *nifH* codes for iron-sulfur protein, and *nifD* and *nifK* determine two subunits of the molybdenum- and iron-containing protein. *nifB, nzjN, nifE,* and nifl involved in the synthesis of the FeMo cofactor of the FeMo protein (*nzfM, nifS, nifu,* and *nifQ*), may also be required for this process. The genetic transformation of rice with *nif* genes should not only ensure their expression but should also protect nitrogenase from inactivation by oxygen and the supply of energy for its functioning. In eukaryotic cells, potential locations for introducing foreign genes are the nucleus, the mitochondrion, and the chloroplast. Of these three locations, the chloroplast appears to provide the most suitable environment for nifgene expression in a plant cell (Merrick and Dixon 1984). The localization of $N_2$ fixation in the chloroplast may allow some of the energy costs of N assimilation to be met through the use of a photosynthetically produced reductant. A method for stable chloroplast transformation in higher plants was reported recently (Staub and Maliga 1992). Recent advances in plant molecular biology allow us to be optimistic about the prospects for transcription of *nif* genes in plants, although the synthesis of an active nitrogenase enzyme is likely to be a far more complex task (see Dixon et al 1993).

## Using apomixis to capture the yield advantage of hybrid rice

Hybrid rice can provide a significant increase (15–20%) in yield over the best inbred lines (Virmani 1994). Yield heterosis results from unknown mechanisms but depends on the fact that in the cells of a hybrid plant every gene is represented by one copy from the male parent and one copy from the female (heterozygous state, Pp). When both copies of certain genes come from one parent (homozygous state, PP or pp), a metabolic or structural weakness may arise in the plant, thus reducing yield. When all genes are in the heterozygous state, these yield-reducing effects are eliminated and a valuable yield advantage is obtained.

Because hybrid rice production is an expensive process, many farmers cannot afford to buy hybrid seed to achieve higher yields. Farmers who buy the seed one year in the hope of reproducing it in their own fields, as they are accustomed to doing with inbred rice, are disappointed. In later generations, the plants show high variability, because at many genetic loci the hybrid genotype (Pp) segregates into three states (PP:Pp:pp = 1:2:l), each with a different phenotype. After 2–3 seasons, the crop shows a diminished yield advantage and becomes less valuable than inbred lines because consistency of growth and quality is lost.

Capturing the yield advantage of hybrid rice may be possible through apomixis, a form of asexual reproduction through seed (Koltunow 1993). In apomictic reproduction, the embryo of the seed forms from maternal tissue rather than from a fertilized egg. As a result, the embryo retains and transmits the heterozygous state of the hybrid. Apomixis will make hybrid rice production faster and cheaper, give breeders more flexibility in the choice of germplasm, lower costs to farmers, and enable farmers to reproduce seed in their own fields (Hanna and Bashaw 1987).

Three main forms of apomixis occur in more than 300 species of flowering plants (Sharma and Thorpe 1995), but they do not occur in cultivated or wild rice (Khush et al 1994). Therefore, it will be necessary to introduce them into rice by genetic engineering. Here we emphasize adventitious embryony and only briefly discuss apospory and diplospory.

### Adventitious embryony in *Citrus*

*Citrus* commonly reproduces by an asexual process called adventitious embryony (Koltunow 1993). The offspring are genetically identical to the maternal parent because the seed embryo derives exclusively from maternal tissue. The tissue is called the nucellus, and in all sexual plants it supplies nutrients to the unfertilized egg and then, after fertilization, to the embryo and endosperm. The adventitious embryo derives not from the fertilized egg cell but from a group of cells (a proembryo) formed in the nucellus (Koltunow et al 1995). This asexual process in *Citrus* keeps the line pure and predictable in its fruiting and other characters, but it prevents *Citrus* breeders from improving their lines through sexual hybridization with a contrasting cultivar.

Rice breeders have the opposite problem. They deal with an exclusively sexual crop that requires several generations to stabilize as elite lines. In the context of hybrid rice, genetic stability would be so advantageous as to be truly revolutionary. The introduction of adventitious embryony into rice by genetic engineering requires the isolation of genes that control the switch from sexuality, but there is little current effort to isolate the genes for adventitious embryony from *Citrus* or any other plant showing this trait. A rather different approach is therefore being tried in conjunction with the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Division of Plant Industry in Australia (Fig. 2): to isolate mutants of *Arabidopsis thaliana* that spontaneously form adventitious embryos (Chaudhury et al 1993), then extract the mutated gene responsible for the switch, and finally transfer the gene to rice. *A. thaliana* is favored for the isolation of mutants because of the ease of producing and screening for mutations and the comparative ease of isolating the mutated gene.

Figure 2 summarizes a three-phase plan to obtain apomixis in rice. IRRI's component is to isolate rice promoters that will enable this switch to be activated in the rice nucellus and nowhere else. If the gene from *A. thaliana* is effective in rice, one or more adventitious embryos should form in the nucellus (as occurs in *Citrus*) and one of these will dominate the others. But what about the sexual embryo? Another task for IRRI in this project is to isolate a promoter that would enable an ablation gene such as a ribonuclease (Mariani et al 1992) to be expressed in the rice egg to inactivate the normal sexual pathway of embryogenesis and leave the adventitious embryo free to interact with the endosperm. This form of adventitious embryony cannot dispense with pollination, because pollination in rice is of the double fertilization type: both the sexual embryo and the endosperm require a sperm cell to activate development. Ablation of the sexual egg will probably not disrupt the fertilization of the polar nuclei of the future endosperm. As a precaution, however, *Arabidopsis* mutants that allow autonomous rather than pseudogamous endospermy will be the source of additional genes for introduction into rice.

## Apospory and diplospory

In addition to adventitious embryony, two other forms of apomixis (diplospory and apospory) may also be usefully transferred into rice. Apospory is particularly interesting because it is the form of apomixis found most commonly in grasses, including close relatives of barley, wheat, maize, millet, and sorghum (Sharma and Thorpe 1995). If current molecular genetic analyses (Ozias-Akins et al 1993, Savidan et al 1994, Sherwood and Gustine 1994) lead to the isolation of genes that control the switch between sexual and aposporous development, those genes could be transferred to rice. Again, apospory depends on the emergence from the nucellus of a special cell or cells capable of forming an embryo.

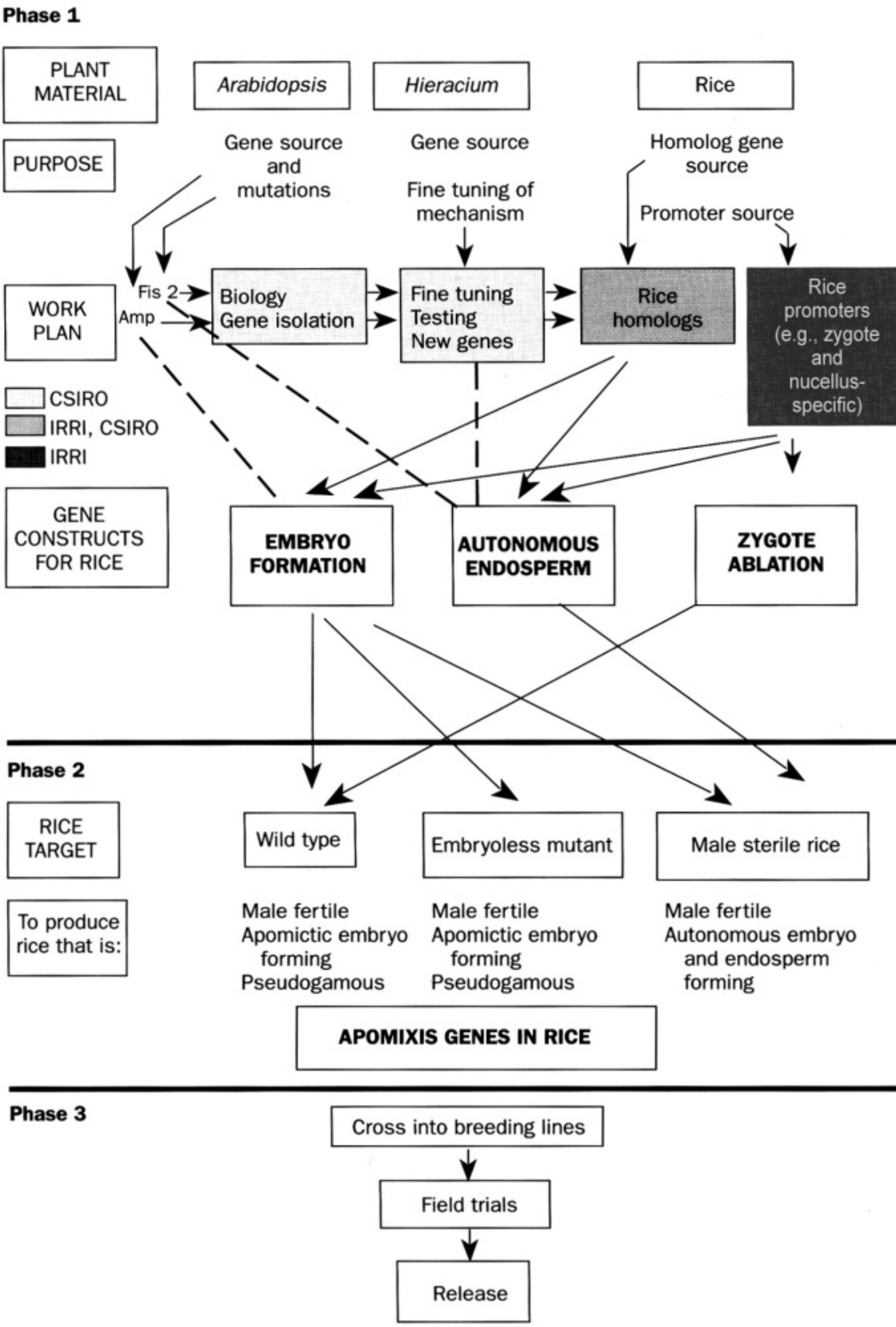



**Fig. 2.** A three-phase plan for engineering apomixis in rice.

*Isolation of apomixis genes of grasses.* IRRI is watching with great interest the research that aims to isolate apomixis genes from aposporous grasses such as *Brachiaria, Cenchrus, Pennisetum,* and *Tripsacum* (Ozias-Akins et al 1993, Savidan et al 1994, Sherwood and Gustine 1994). Because of genetic evidence suggesting that apospory is controlled by only one or a few genes, we expect that the new tools of molecular genetics and genome analysis will enable us to isolate these genes. Segregating populations of crosses between apomicts and their sexual relatives will probably lead to precise genetic mapping of the genes that control the switch between sexuality and apospory, and physical mapping of the genome will eventually allow us to isolate the relevant genes. But the rice genome is much smaller than the genomes of other cereals and may be a useful reference genome for chromosome walking. The partial preservation of the relative location of genes in long stretches of cereal genomes (synteny) makes this reference role of rice possible.

*Diplospory.* In grasses, diplospory is less common than apospory, but it is nevertheless widespread in flowering plants. It does not directly involve the nucellus; rather, it involves an aberration of the sexual pathway that prevents meiosis. Normally, two meiotic divisions convert a diploid megaspore mother cell (Pp) into a tetraploid cell (PPpp) and then into a tetrad of haploid cells, represented as P/P/p/p. One of these tetrads (P or p) then undergoes three mitoses to form the 2-, 4-, and then 8-nucleate embryo sacs, the last of which is ready for fertilization. In diplospory, the megaspore mother cell remains diploid (Pp), thus retaining the heterozygous state. To achieve diplospory in rice, we would have to eliminate meiosis in the megaspore mother cell and promote parthenogenesis and autonomous endospermy or pseudogamy in the diploid embryo sac.

### Apomixis and control of the cell cycle

Whichever form of apomixis is attempted for rice, a fuller knowledge of the control of the cell cycle in plants is required. One of the aims of the New Frontier Project on Apomixis will be to ensure that we learn more about this crucial aspect of plant development. But any interruptions of the cell cycle that are introduced in the nucellus, the megaspore mother cell, or the egg to achieve apomixis must not interfere with cell division in other cells. Our ability to identify and isolate promoters truly specific for these cells will be crucial to the success of the project.

## A perennial rice to improve sustainability in the uplands

Because of high increases in population and migration, land pressure intensified in the uplands of Southeast Asia and severe erosion problems arose in areas with steep slopes and heavy rains. In those areas, where most people are at subsistence income levels (IRRI 1995), stable cropping systems and increased productivity are necessary to control erosion, ensure food security, and stop deforestation (Trung et al 1995).

Perennial grains represent an environment-friendly alternative for use on erodible land where annual crop production is not sustainable (Wagoner 1990). Developing perennial grains is not a new idea and different approaches have been used in the

Gramineae (see Wagoner 1990, for a review). Wide hybridization began in the early 20th century, intending to transfer to cultivated species the perennial traits from a related wild species. Interspecific hybridization has been used in sorghum (Piper and Kulakow 1994) and rye (Reimann-Philipp 1986). and intergeneric hybridization in wheat (Dewey 1984, Sharma and Gill 1983). But despite these efforts, few results have been obtained and more research is needed before commercial cultivars can be released. Domestication is another approach in which selection is made in wild populations in order to improve their agronomic value, mainly productivity and resistance to shattering. The use of this approach is more recent and has focused on some perennial grasses with good yield potential, such as smooth bromegrass (*Bromus inermis*) (Knowles et a1 1970), wildrye (Leymus racemosus) and eastern gamagrass (Tripsacum *dactyloides*) (Piper and Towne 1988), and intermediate wheatgrass (*Thinopyron intermedium*) (Knowles 1977, Wagoner 1990, 1994).

The main concern arising when developing perennial cereals is the general trade-off between perenniality and grain production because of differences in allocation of resources between perennial and annual plants. The physiological possibility of combining good agronomic quality (stable yield, no shattering, good grain quality) with the ability to persist several years may be questioned. In developing an overwintering sorghum by crossing *Sorghum bicolor* with the wild species *S. halepense* to transfer the rhizomes of the latter species into the cultivated one, however, Piper and Kulakow (1994) found no negative correlation between seed production and rhizome production.

## Use of wild perennial rice

In rice, no attempt has been made to develop a cultivated perennial form, although some wild perennial species have been used for food. At the beginning of the 20th century, grains of the perennial species Oryza longistuminata were harvested in the wild and constituted an important complementary food in the lower Senegal River (Porteres 1949). Populations from the swamplands of West and Central Africa, although considered relatively low seed setters, may still be harvested in sufficient quantities to appear in markets (Harlan 1989). In India and Brazil, seeds of *O. rufipogon* and 0. glumaepatuZa (the name used for Latin American populations of *O. rufipogon),* respectively, are sometimes collected and eaten like rice (Vaughan 1994). In Cambodia, 0. rufipogon has recently been used as food during famine (Vaughan and Sitch 1991).

## Sources of perenniality

Many wild *Oryza* species are potential sources of perenniality. Two species, 0. *rujipogon* and 0. longistaminata, are closely related to *O.* sativa—they have the same A genome—and represent good donor candidates. *O. rujipogon* can be easily crossed with the cultivated rice. Although a crossing barrier caused by two complementary dominant lethal genes exists between *O. longistaminata* and the other *Oryza* species with the A genome, it can be overcome using embryo rescue techniques to produce $F_1$ hybrids (Chu and Oka 1970).

*Oryza rufipogon* is an Asian species in which perenniality is attributed to a vegetative crown that allows permanent tillering and ratooning (Vaughan 1994), and to the production of stolons. Variation in the expression of perenniality between populations is continuous, from annual forms adapted to habitats with variable water status to perennial populations that grow in permanently flooded areas.

*Oryza longistaminata* is an African species with vigorous rhizomes. Though growing preferentially in permanently flooded environments, it is also found in ponds occasionally dried during the dry season; the rhizomes act as storage organs and produce new shoots at the beginning of the next rainy season (Porteres 1949, Second et al 1977).

## Approaches to developing a cultivated perennial rice

*Interspecific hybridization.* In *O. longistaminata,* rhizomes have been shown to provide adaptation to drought both in natural conditions in Africa (Second et al 1977) and in a greenhouse experiment conducted at IRRI from November 1995 to June 1998. *O. longistaminata* is being used in an interspecific hybridization program to incorporate the perennial trait into *O. sativa.* The objective is to produce material with rhizomes of intermediate length that can be planted in hedgerows and remain confined within a determined space, therefore decreasing the risk of that rice becoming a weed in nearby irrigated fields. Figure 3 shows the breeding strategy designed to avoid the crossing barrier, which is linked with the presence of rhizomes (Ghesquière 1991), while maintaining a reasonable expression of the rhizomes. When backcrossing $F_1$ *O. sativa/O. longistaminata* hybrids to *O. sativa,* rhizomes are definitely lost. Intercrossing backcross hybrids has proved to be a suitable strategy to keep rhizomes while progressively increasing the proportion of *O. sativa* genome in the product and improving its agronomic traits.

*Oryza rufipogon* is generally more susceptible to drought than *O. longistaminata,* but individuals from that species with good ability to survive drought have also been selected in the greenhouse and have been crossed with upland cultivars. The progenies are being tested for perenniality under field conditions.

*Domestication. O. longistaminata* populations naturally introgressed with genes from *O. sativa* have been observed and collected in many African countries (Ghesquière 1988). Introgressed individuals showing shorter rhizomes and higher seed productivity than true wild *O. longistaminata* have been selected at IRRI from two populations collected in Ethiopia and Tanzania, respectively. Their progenies are being evaluated under greenhouse conditions.

*Use of molecular markers.* Perenniality is a complex trait and its genetic control is still poorly understood. Molecular markers are being used to better understand the genetic control of perenniality and related traits. Markers linked with the genes responsible for perenniality will be used subsequently in marker-aided selection. Two different interspecific populations segregating for rhizome expression have been de-

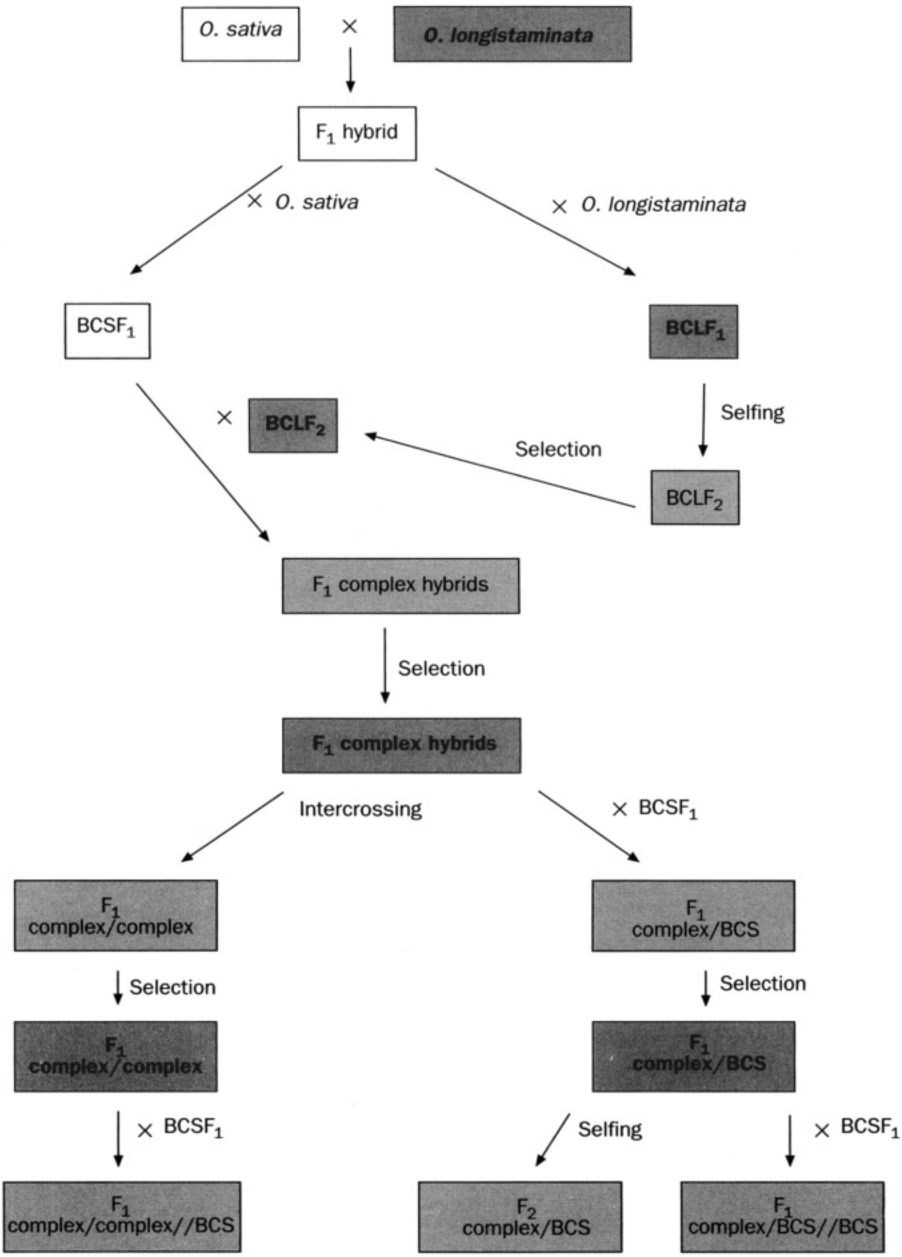



**Fig. 3.** Breeding scheme for transferring the rhizome trait from *O. longistaminata* to *O. sativa*. (☐ = no rhizomes, ▒ = segregation for rhizome expression, ■ = 100% rhizomes.)

veloped: a $BC_1F_2$ population obtained by selfing $F_1$ hybrids from one backcross on *O. longistaminata* ($BC_1LF_1$) and an intercross population produced by intercrossing $BC_1LF_1$ individuals (McNally et al 1998). These populations are being mapped using RFLP and STS markers and phenotyped for rhizome expression. Probes that are known to be affiliated with perenniality in sorghum (Paterson et al 1995, Chittenden et al 1994) are used.

### Incorporating resistance to nematodes

Nematodes are an important constraint in the uplands, and only two methods of control are economically and environmentally acceptable: rotation with nonhost crops and varietal resistance (Prot 1996). In perennial rice, however, only varietal resistance can be used. The level of resistance to one of the most damaging species, the root-knot nematode *Meloidogyne graminicola,* is low in *O. sativa,* but one accession of *O. longistaminata* used to develop a perennial upland rice has been found to be highly resistant to that nematode species (Soriano et al 1998). A genetic study of the resistance is under way. The mapping populations developed to study the genetic control of perennial traits are also segregating for nematode resistance and phenotyping is ongoing for that trait too. Identifying markers linked with the gene(s) responsible for resistance to *M. graminicola* will greatly facilitate further selection aiming to incorporate the resistance into perennial rice and into annual upland cultivars.

## Barriers to yield increases: a modeling approach

Ultimately, significant improvements in the yield of tropical rice will result from what we call "breaking the barrier." Modeling work has indicated that the yield barrier has two major parts; each comprises a closely linked series of obstacles (Fig. 4). A major yield increase will not be achieved unless both parts of the yield barrier are broken. The first part simply consists of increasing the volume, or number, of the viable spikelets per unit ground area. The second part consists of filling that volume with the appropriate elemental structures.

### Part 1 number of viable spikelets

First let us deal with the problem of increasing the size of the sink. The number of spikelets depends on the number of panicles per unit ground area and the number of spikelets per panicle. The panicles are not homogeneous as they are borne on tillers that vary in age and size. Let us assume that the average hill can be characterized in terms of spikelet numbers and that the crop consists of a number of average hills. At panicle initiation, the potential number of spikelets is represented by the number of developing primordia and, under ideal management, this number represents the "genetic potential" of the variety. At high temperatures, such as those experienced in tropical Asia, many young, developing primordia are eventually lost through floret abortion on rice plants. This loss is mainly brought about because the synthetic demands for resources are driven by temperature and they exceed the maximum rate of supply of those resources from the leaves and roots of the rice plants. The effects of

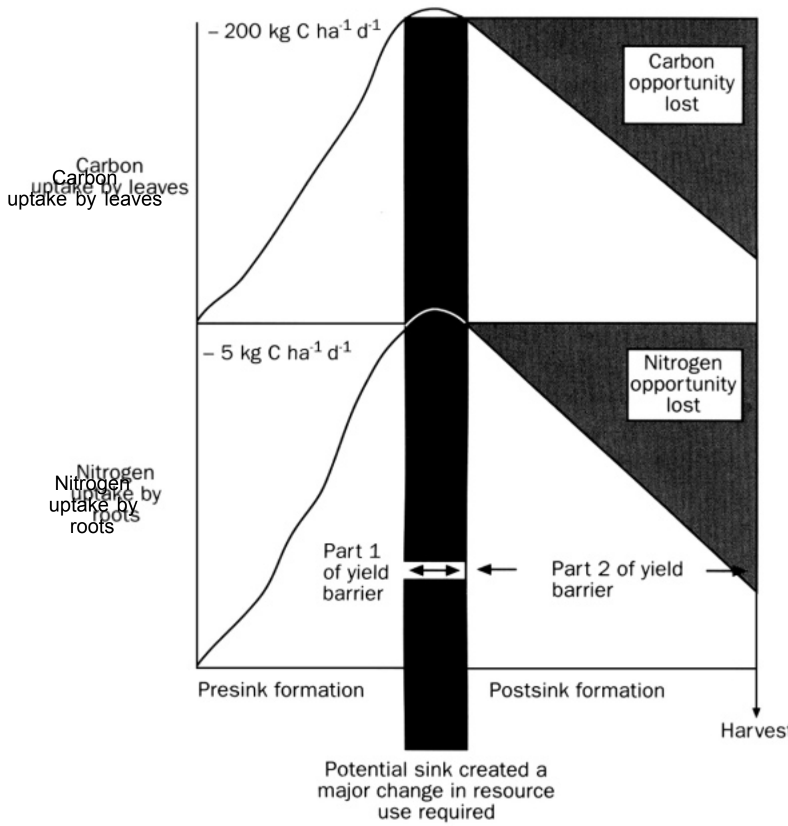



**Fig. 4.** Development of the rice plant showing the capture of C and N as the plant grows toward maturity. The two parts of the yield barrier are shown. During the first barrier period, size of the sink is determined; during the second barrier period, the sink is filled.

increasing temperatures on rice yields are ubiquitous. At an enzymatic level, increasing temperature not only increases the rate of biochemical processes but also destroys the structural integrity of the enzymes involved in those processes. If the supply of carbon and nitrogen cannot be increased because of fundamental limitations imposed by the photosynthetic system, then the rate of demand for them must be lowered to prevent the abortion and loss of potential grains. The classical way of bringing supply and demand into balance is to alter the structure of the plant so that less assimilate is invested in the stem and sheath and more is available to meet the demands of the developing sink. The temperature sensitivity of the synthetic enzymes involved in reproductive growth probably varies. Another way of balancing supply and demand would be to identify plants containing less thermally sensitive enzymes and to incorporate the genes responsible for their synthesis into elite material. A third and much explored approach is to find plants that have higher resource-capture abilities and to include such material in breeding programs.

### Part 2: filling the sink

To achieve yield potential following an increase in sink size, we have to overcome the second part of the yield barrier: filling the sink. A 50% loss of physiological efficiency in rice plants occurs soon after the sink is created. Model calculations show a loss in mineral element capture through the roots and a 50% decline in canopy photosynthesis during the grain-filling period. The reasons for the loss in efficiency are obscure, but the loss may be linked to signals sent to the roots at the onset of reproductive growth. We need to identify and modify the genetic characters involved in this loss.

To grow higher-yielding rice plants in the tropics, we need genotypes that can maintain a better balance between thermally driven demands of synthetic enzymes and enzymes involved in supplying the resources needed to form and fill the spikelets. Furthermore, we must give some attention to the influence of high temperature on pollination. We need genetic material with a range of thermally sensitive reproductive systems. Plant architecture must also be emphasized because it influences the availability of resources during reproductive growth. Leaf architecture may also influence the efficiency with which matter and energy are exchanged with the gaseous environment.

## Conclusions

New Frontier Projects currently extend beyond the pipeline that carries research recommendations and products from the laboratory into farmers' fields. Products can be expected in 10–15 years or even longer. Meanwhile, the success of these projects must be judged in terms of whether they clarify the way we look at important but difficult problems, whether they identify and evaluate alternative ways forward, whether they predict and remove roadblocks, and whether they create a sense of scientific excitement to attract the best collaborators to each effort.

## References


Ardourel M, Demont N, Debellé F, Maillet F, de Billy F, Promé JC, Dénarié J, Truchet G. 1994. *Rhizobium meliloti* lipooligosaccharide nodulation factors: different structural requirements for bacterial entry into target root hair cells and induction of plant symbiotic developmental responses. Plant Cell 6(10):1357-1374.

Barraquio WL, Revilla L, Ladha JK. 1997. Isolation of endophytic diazotrophic bacteria from wetland rice. Plant Soil 194:15-24.

Boddey RM, de Oliveira OC, Urquiaga S, Resi VM, de Olivares FL, Baldani VLD, Dobereiner J. 1995. Biological nitrogen fixation associated with sugar cane and rice: contributions and prospects for improvement. Plant Soil 174:195-209.

Chaudhury AM, Letham S, Craig S, Dennis ES. 1993. *amp1*-a mutant with high cytokinin levels and altered embryonic pattern, faster vegetative growth, constitutive photomorphogenesis and precocious flowering. Plant J. 4:907-916.

Chittenden LM, Schertz KF, Lin RA, Wing RA, Patterson AH. 1994. A detailed RFLP map of *Sorghum bicolor* x *S. propinquum,* suitable for high-density mapping, suggests ancestral duplication of *Sorghum* chromosomes or chromosomal segments. Theor. Appl. Genet. 87:925-933.

Chu YE, Oka HI. 1970. The genetic basis of crossing barriers between *O. perennis* subsp. *barthii* and its related taxa. Evolution 24:135-144.

Cocking EC, Al-Mallah MK, Benson E, Davey MR. 1990. Nodulation of non-legumes by rhizobia. In: Gresshoff PM, Roth LE, Stacey G, Newton WE, editors. Nitrogen fixation: achievements and objectives. London: Chapman and Hall. p 813-823.

Cocking EC, Davey MR, Kothari SL, Srivastava JS, Jing J, Ridge RW, Rolfe BG. 1992. Altering the specificity control of the interaction between rhizobia and plants. Symbiosis 14:123-130.

Cocking EC, Srivastava JS, Cook JM, Kothari SL, Davey MR. 1993. Studies on the nodulation of maize, wheat, rice and oilseed rape: interactions of rhizobia with emerging lateral roots. International Symposium on Nitrogen Fixation with Non-leguminous Crops, Shandong University, Jinan, China. p 59-65.

de Jong AJ, Heidstra R, Spaink HP, Hartog MV, Meijer EA, Hendriks T, Lo Schiavo F, Terzi M, Bisseling T, van Kammen A, de Vries SC. 1993. *Rhizobium* lipooligosaccharides rescue a carrot somatic embryo mutant. Plant Cell 5:615-620.

Dewey DR. 1984. The genomic system of classification as a guide to intergeneric hybridization with the perennial Triticae. In: Gustafson JP, editor. Gene manipulation in plant improvement. New York (USA): Plenum Press. p 209-279.

Dixon R, Vanderleyden J, Romero D, Boddey RM, Cocking EC, Dénarié J, Elmerich C, Rolfe BG, Sprent J. 1993. Extension of nitrogen fixation to other crops. In: Palacios R, Mora J, Newton WE, editors. New horizons in nitrogen fixation. Netherlands: Kluwer Academic Publishers. p 765-768.

Dobereiner J, Baldani VLD, Olivares F, Reis VM. 1994. Endophytic diazotrophs: the key to BNF in graminaceous plants. In: Hegati NA, Fayez M, Monib M, editors. Nitrogen fixation with non-legumes. Cairo (Egypt): American University in Cairo Press. p 395-408.

Ghesquière A. 1988. Diversité génétique de l'espéce sauvage de riz, *Oryza longistaminata* A. Chev. et Roehr et dynamique des flux géniques au sein du groupe *Sativa* en Afrique. Thésé d'Etat. Université Paris XI, Orsay. 228 p.

Ghesquière A. 1991. Reexamination of genetic control of the reproductive barrier between *Oryza longistaminata* and *O. sativa,* and relationship to rhizome expression. In: Proceedings of the 2nd International Rice Genetics Symposium, 14-18 May 1990. Los Baños (Philippines): International Rice Research Institute. p 729-730.

Hanna WW, Bashaw EC. 1987. Apomixis: its identification and use in plant breeding. Crop Sci. 27:1136-1139.

Harlan JR. 1989. Wild-grass seed harvesting in the Sahara and Sub-Sahara of Africa. In: Harris DR, Hillman GC, editors. Foraging and farming, the evolution of plant exploitation. Boston, Mass. (USA): Unwin Hyman. p 79-98.

IRRI (International Rice Research Institute). 1995. Program report for 1994. Manila (Philippines): IRRI. 311 p.

Khush GS, Bennett J, editors. 1992. Nodulation and nitrogen fixation in rice: potential and prospects. Manila (Philippines): International Rice Research Institute.

Khush GS, Brar DS, Bennett J, Virmani SS. 1994. Apomixis for rice improvement. In: Khush GS, editor. Apomixis: exploiting hybrid vigor in rice. Manila (Philippines): International Rice Research Institute. p 1-21.

Knowles RP. 1977. Recurrent mass selection for improved seed yields in intermediate wheatgrass. Crop Sci. 17:51-54.
Knowles RP, Cooke DA, Buglass E. 1970. Breeding for seed yield and seed quality in smooth bromegrass, *Bromus inermis* Leyss. Crop Sci. 10:539-542.
Koltunow AM. 1993. Apomixis: embryo sacs and embryos formed without meiosis or fertilization in ovules. Plant Cell 5:1425-1437.
Koltunow AM, Soltys K, Nito N, McClure S. 1995. Anther, ovule, seed and nucellar embryo development in *Citrus sinensis* cv Valencia. Can J. Bot. 73:1567-1582.
Ladha JK, de Bruijn FJ, Malik KA. 1997. Introduction: assessing opportunities for nitrogen fixation in rice - a frontier project. Plant Soil 194:l-10.
LaRue TA, Weeden NF. 1994. The symbiosis genes of the host. First European Nitrogen Fixation Conference, Szeged, Hungary.
Mariani C, Gossele V, de Beuckeleer M, de Block M, Goldberg RB, de Greef W, Leemans J. 1992. A chimaeric ribonuclease-inhibitor gene restores fertility to male sterile plants. Nature 357:384-387.
McNally KL, Schmit V, Courtois B. 1998. Towards a perennial upland rice. Philip. J. Crop Sci. 23(Suppl. 1):64. (Abstr.)
Menick M, Dixon R. 1984. Why don’t plants fix nitrogen? Trends Biotech. 2:162-166.
Mylona P, Pawlowski K, Bisseling T. 1995. Symbiotic nitrogen fixation. Plant Cell 7:869-885.
Olivares FL, Janes EK, Reis VM, Baldani VLD, Baldani JI, Dobereiner J. 1993. Colonization of vascular tissue by *Herbaspirillum* spp. in sorghum and sugar cane. Fitopatolog. Bras. 18(Suppl. 290):313.
Ozias-Aluns P, Lubbers EL, Hanna WW, McNay JW. 1993. Transmission of the apomictic mode of reproduction in *Pennisetum:* co-inheritance of the trait and molecular markers. Theor. Appl. Genet. 85:632-638.
Paterson AW, Schertz KF, Lin Y-R, Liu S-C, Chang Y-L. 1995. The weediness of wild plants: molecular analysis of genes influencing dispersal and persistence of johnsongrass, *Sorghum halepense* (L.) Pers. Proc. Natl. Acad. Sci. USA 92:6127-6131.
Piper JK, Kulakow PA. 1994. Seed yield and biomass allocation in *Sorghum bicolor* and $F_1$ and backcross generations of *S. bicolor* x *S. halepense* hybrids. Can. J. Bot. 72:468-474.
Piper JK, Towne D. 1988. Multiple year patterns of seed yield in five herbaceous perennials. Land Inst. Res. Rep. 5:14-17.
Porteres R. 1949. Le riz vivace de 1’Afrique (*Oryza barthii* A. Chev.). Agron. Trop. 4(1-2):5-24.
Prot J-C. 1996. Nematode pests in upland rice production systems. In: Piggin C, Courtois B, Schmit V, editors. Upland rice research in partnership. IRRI Discussion Paper Series No. 16. Manila (Philippines): International Rice Research Institute. p 239-245.
Reddy PM, Kouchi H, Hata S, Ladha JK. 1996. Homologs of *GmENOD93* from rice. In: Proceedings of 8th International Congress on Molecular Plant-Microbe Interactions, 14-19 July 1996, Knoxville, Tenn. (Abstr.).
Reddy PM, Ladha JK, So R, Hernandez R, Ramos MC, Angeles OR, Dazzo FB, de Bruijn FJ. 1997. Rhizobia1 communication with rice roots: induction of phenotypic changes, mode of invasion and extent of colonization. Plant Soil 194:81-98.
Reddy PM, Ladha JK, Ramos MC, Hernandez R, Torrizo L, Datta SK, Datta K. 1998. Nod factors activate *MtENOD* 12 gene expression in rice. Plant J. (In press.)
Reimann-Philipp R. 1986. Perennial spring rye as a crop alternative. J. Agron. Crop Sci. 157:281-285.

Sandhu GR, Aslam Z, Salim M, Sattar A, Qureshi RH, Ahmed N, Jones RGW. 1981. The effect of salinity on the yield and composition of *Diplachne fusca* (Kallar grass). Plant Cell Environ. 4: 177-181.
Savidan Y, Leblanc O, Berthaud J. 1994. Transferring apomixis to maize. In: Khush GS, editor. Apomixis: exploiting hybrid vigor in rice. Manila (Philippines): International Rice Research Institute. p 23-29.
Second G, Bezançon G, Bozza J. 1977. Variabilité d' *O. longistaminata* et du complexe sativa des *Oryza* en Afrique: aspects écologiques et évolutifs. In: Réunion sur les espéces africaines de riz, 25-26 Janvier 1977. Paris (France): IRAT-ORSTOM. p 47-55.
Sharma HC, Gill BS. 1983. Current status of wide hybridization in wheat. Euphytica 32:17-31.
Sharma KK, Thorpe TA. 1995. A sexual embryogenesis in vascular plants in nature. In: Thorpe TA, editor. *In vitro* embryogenesis in plants. Kluwer Academic Publishers. p 17-72.
Sherwood RT, Gustine DL. 1994. Modifying embryo sac development and strategies for cloning the apomixis gene from buffelgrass. In: Khush GS, editor. Apomixis: exploiting hybrid vigor in rice. Manila (Philippines): International Rice Research Institute. p 47-50.
Soriano I, Schmit V, Brar DS, Prot J-C, Reversat G. 1998. Resistance to rice root-knot nematode *M. graminicola* identified in *Oryza longistaminata* and *O. glaberrima*. Submitted.
Staub JM, Maliga P. 1992. Long regions of homologous DNA are incorporated into the tobacco plastid genome by transformation. Plant Cell 4:39-45.
Stoltzfus S, So R, Malarvizhi M, Ladha JK, de Bruijn FJ. 1997. Isolation of endophytic bacteria from rice and assessment of their potential for supplying rice with biologically fixed nitrogen. Plant Soil 194:25-36.
Trinick MJ. 1973. Symbiosis between rhizobium and non-legumes, *Trema aspera*. Nature 244:459-460.
Trung H, Thuyet L, Tho T, Thieng N. 1995. Strengthening food production: an urgent measure in upland rice ecosystems of the mountainous ethnic regions of Vietnam. In: Fragile lives in fragile ecosystems. Proceedings of the International Rice Research Conference, 13-17 Feb 1995, Los Baños, Philippines. Manila (Philippines): International Rice Research Institute. p 459-466.
Vance CP. 1990. Symbiotic nitrogen fixation: recent genetic advances. In: Stumpf PK, Conn EE, editors. The biochemistry of plants: a comprehensive treatise. New York (USA): Academic Press. p 43-88.
Vaughan DA. 1994. The wild relatives of rice. Manila (Philippines): International Rice Research Institute. 137 p.
Vaughan DA, Sitch LA. 1991. Gene flow from the jungle to farmers. Bioscience 41(1):22-28.
Virmani SS. 1994. Hybrid rice technology: new developments and future prospects. Manila (Philippines): International Rice Research Institute.
Wagoner P. 1990. Perennial grain development: past efforts and potential for the future. Crit. Rev. Plant Sci. 9(5):381-409.
Wagoner P. 1994. Perennial grain: a new use for intermediate wheatgrass. New Crops News-Newsl. Indiana Ctr. New Crops Plant Prod. 4(2).
Yang W-C, de Blank C, Meskiene I, Hirst H, Bakker J, van Kammen A, Franssen H, Bisseling T. 1994. *Rhizobium* Nod factors reactivate the cell cycle during infection and nodule primordium formation, but the cycle is only completed in primordium formation. Plant Cell 6:1415-1426.

## Notes

*Authors' address:* International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines. j.bennett@cgnet.com j.ladha@cgnet.com v.schmit@cgnet.com j.sheehy@cgnet.com

*Citation:* Dowling NG, Greenfield SM, Fischer KS, editors. 1998. Sustainability of rice in the global food system. Davis, Calif. (USA): Pacific Basin Study Center, and Manila (Philippines): International Rice Research Institute.

# Part IV: Rice Production Systems: Biodiversity

CHAPTER 15

# Protecting the diversity of tropical rice ecosystems

K.S. Fischer

From when it was first gathered by humans 12,000 years ago and first cultivated 6,000 years ago, rice (genus *Oryza*) has fed more people over a longer period than any other crop. Rice has been linked closely with the evolution of human society, both as a commercial product and as a creator of communities. All the scriptures of Asia's ancient civilizations mention rice, and it is involved in the religious and secular ceremonies of many countries—from birth, through marriage, to death—and in colloquial speech. Rice has also been traded in all directions from its places of origin, and it is now cultivated on every continent except Antarctica. Irrigated rice, which has always depended on a well-regulated, adequate water supply, necessitated the building of canals, reservoirs, and terraces and the use of a large labor force, which in turn created a demand for the nearby availability of human settlements to ensure a basic food supply.

Because rice plays such an important role in the lives of its producers and consumers, it is little wonder that it occupies a major position in the cultures of rice-growing countries. Rice and the rice ecosystem have a rich diversity—cultural and biological—that must be prudently managed because the permanency of the food base on which we all rely, today and for generations to come, depends on our care and use of the genetic diversity of rice and our stewardship of natural resources (Huggan 1995).

Today, we estimate that rice is the staple food for about 2.4 billion people, providing more than 20% of their daily calorie intake. By the middle of the 21st century, this number will increase to 4.6 billion. But not many economists or policymakers are willing to look that far into the future. With the speed of change we are experiencing, it has become increasingly difficult to develop solid, long-term strategies that can serve as a foundation for planning biological research. Thirty years ago, for example, a transgenic rice plant was not even a dream.

The use and conservation of biological diversity, now known as biodiversity, have become a focus of concern for human society in recent decades. Biodiversity is multifaceted and has many definitions. In brief, it is the "variety of life forms, the ecological roles they perform, and the genetic diversity they contain" (Wilcox 1984). For agroecosystems, as for other ecosystems, biodiversity spans hierarchies from the landscape to species to genes.

From the standpoint of species-level biodiversity, Pimentel et al (1992) convincingly show that most invertebrate biodiversity exists in crop fields, forests, and other managed ecosystems. Yet Western thinking has led many ecologists to conclude that agroecosystems have simple dynamics and internal structures, are impoverished in species, are evolutionarily recent, and are inherently uninteresting (Kogan 1986, Paul and Robertson 1989, Settle et al 1966, Harris and Roger 1988).

Tropical rice ecosystems present an exceptional case (Settle et al 1996). For example, counts of macroinvertebrate taxa alone for conventional-cropped Philippine and Indonesian rice fields exceed 600 and 760, respectively (Schoenly et al 1996, Settle et al 1996). These numbers rival estimates for species richness and community complexity of many inventoried natural ecosystems in North America and Europe (Pimentel et al 1992). Moreover, rice's more than 6,000 years of cultivation (Chang 1976), its geographically extensive distribution, and the relatively a seasonal warm and humid climate of tropical Asia have created conditions that favor increased pest and natural enemy specialization in rice, multiple insect generations per season, and 2–3 cropping seasons per year. These conditions, when taken together and compared to other evolutionarily recent fauna (introduced Hawaiian *Drosophila,* Carson and Kaneshiro 1976; Galapagos finches, Grant and Grant 1989), have provided sufficient time for evolutionary events (e.g., natural selection) to have occurred in tropical rice ecosystems. Future agricultural policies promise to promote greater use of biodiversity through initiatives that are ecologically and economically sound and that integrate whole-ecosystem management globally (Pimentel et al 1992).

The following two chapters by Bellon et al and Schoenly et al describe the use and management of two areas of biodiversity—genetic diversity of the rice gene pool and indigenous biota of rice landscapes.

## References


Carson HL, Kaneshiro KY. 1976. *Drosophila* of Hawaii: systematics and ecological genetics. Annu. Rev. Ecol. Sys. 7:311-345.

Chang 7T. 1976. The origin, evolution, cultivation, dissemination, and diversification of Asian and African rices. Euphytica 25:435-441.

Grant BR, Grant PR. 1989. Evolutionary dynamics of a natural population: the large cactus finch of the Galapagos. Chicago (USA): University of Chicago Press. 350 p.

Harris MK, Roger CE, editors. 1988. The entomology of indigenous and naturalized systems in agriculture. Boulder, Colo. (USA): Westview Press.

Huggan RD. 1995. Co-evolution of rice and humans. GeoJournal 35:262-274.

Kogan M, editor. 1986. Ecological theory and integrated pest management practice. New York (USA): John Wiley and Sons. 362 p.

Paul EA, Robertson GP. 1989. Ecology and the agricultural sciences: a false dichotomy? Ecology 70:1594-1597.

Pimentel D, Stachow U, Takacs DA, Brubaker HW, Dumas AR, Meaney JJ, O'Neil JAS, Onsi DE, Corzilius DB. 1992. Conserving biological diversity in agriculturallforestry systems. BioScience 42:354-362.

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

Settle WH, Ariawan H, Tri Astuti E, Cahyana W, Hakim AL, Hindayana D, Sri Lestari A, Pajarningsih, Sartanto. 1996. Managing tropical rice pests through conservation of generalist natural enemies and alternative prey. Ecology 77:1975-1978.

Wilcox BA. 1984. In situ conservation of genetic resources: determinants of minimum area requirements. In: McNeeley JA, Miller KR, editors. National parks, conservation and development: the role of protected areas in sustaining society. Washington, D.C. (USA): Smithsonian Press. p 639-647.

## Notes

*Author's address:* International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines. k.fischer@cgnet.com

*Citation:* Dowling NG, Greenfield SM, Fischer KS, editors. 1998. Sustainability of rice in the global food system. Davis, Calif. (USA): Pacific Basin Study Center, and Manila (Philippines): International Rice Research Institute.

CHAPTER 16

# Rice genetic resources

M.R. Bellon, D.S. Brar, B.R. Lu, and J.L. Pham

The use and conservation of biodiversity are increasingly important concerns for society. In this paper, we focus on the genetic diversity aspects of biodiversity as they pertain to the rice gene pool and its contribution to agriculture and our food supply. We review what is known about the rice gene pool and the need to conserve it. We investigate the threats and challenges that conservation of rice genetic diversity faces from changing socioeconomic and cultural conditions, as well as from the development and widespread adoption of modern varieties. We analyze the different conservation strategies that have been developed, emphasizing their strengths and weaknesses. We also examine the use of rice genetic diversity, from the perspectives of both farmers and breeders. Finally, we deal with current policy issues associated with the conservation and use of the rice gene pool, such as intellectual property rights and the Convention on Biological Diversity, and discuss the challenges ahead.

The use and conservation of biodiversity have become a focus of concern for human society in recent decades. Biodiversity is multifaceted and has many definitions, but according to the *Global Biodiversity Assessment*—a comprehensive volume written by an international group of leading scientists on biodiversity—it can be defined as the total diversity and variability among systems and organisms at the bioregional, landscape, ecosystem, and habitat levels, at the various organismic levels down to species, populations, and individuals, and at the level of the population and genes (Heywood 1995). For agroecosystems, as for other ecosystems, biodiversity spans several hierarchies, from the landscape to genes. This chapter deals with the genetic diversity aspects of biodiversity as they pertain to the rice gene pool and its contribution to agriculture and our food supply.

## The rice gene pool

Rice is an economically important cereal crop, providing food for more than half of the world's population. There are two cultivated species of rice in the world, which are members of a group of more than 20 grass species included in the genus *Oryza* (Table 1) of the family Poaceae. Asian rice (*Oryza sativa*) had its origin in South and Southeast Asia and is now cultivated worldwide, whereas African rice (*O. glaberrima*)

Table 1. **Taxa in the genus *Oryza:* the species complexes, chromosome numbers, genome groups, and distribution are modified from Vaughan (1989). GG and HHJJ genomes were recently identified by Aggarwal et al (1997).**

| Complex/species | 2n | Genome | Distribution | Useful or potentially useful traits |
|---|---|---|---|---|
| *O. sativa* complex | | | | |
| *O. barthii* A. Chev. | 24 | AA | Africa | Resistance to green leafhopper and bacterial blight, drought avoidance |
| *O. glaberrima* Steud. | 24 | AA | West Africa | Cultigen |
| *O. glumaepatula* Steud. | 24 | AA | South & Central America | Elongation ability, source of cytoplasmic male sterility |
| *O. longistaminata* Chev. et Roehr. | 24 | AA | Africa | Resistance to bacterial blight, drought tolerance |
| *O. meridionalis* Ng | 24 | AA | Tropical Australia | Elongation ability, drought avoidance |
| *O. nivara* Sharma et Shastry | 24 | AA | Tropical & subtropical Asia | Resistance to grassy stunt virus, blast, and stem rot, drought avoidance |
| *O. rufipogon* Griff. | 24 | AA | Tropical & subtropical Asia, tropical Australia | Elongation ability, resistance to bacterial blight, sheath spot, source of cytoplasmic male sterility |
| *O. sativa* L. | 24 | AA | Worldwide | Cultigen |
| *O. officinalis* complex | | | | |
| *O. australiensis* Domin | 24 | EE | Tropical Australia | Drought tolerance, resistance to brown planthopper |
| *O. alta* Swallen | 48 | CCDD | South and Central America | Resistance to striped stem borer, high biomass production |
| *O. eichingeri* Peter | 24, 48 | CC | South Asia & East Africa | Resistance to yellow mottle virus, brown planthopper, whitebacked planthopper, green leafhopper |
| *O. grandiglumis* (Doell) Prod. | 48 | CCDD | South & Central America | High biomass production |
| *O. latifolia* Desv. | 48 | CCDD | South & Central America | Resistance to brown planthopper, high biomass production |
| *O. minuta* J.S. Presl. ex C.B. Presl. | 48 | BBCC | Philippines & Papua New Guinea | Resistance to sheath blight, bacterial blight, blast, brown planthopper, green leafhopper, whitebacked planthopper |
| *O. officinalis* Wall ex Watt | 24 | CC | Tropical & subtropical Asia, tropical Australia | Resistance to thrips, brown planthopper, green leafhopper, whitebacked planthopper |
| *O. punctata* Kotschy ex Steud. | 24, 48 | BB, BBCC | Africa | Resistance to brown planthopper, zigzag leafhopper |
| *O. rhizomatis* Vaughan | 24 | CC | Sri Lanka | Drought tolerance, rhizomatous |
| *O. meyeriana* complex | | | | |
| *O. granulata* Nees et Arn. ex Watt | 24 | GG | South & Southeast Asia | Shade tolerance, adaptation to aerobic soil |
| *O. meyeriana* (Zoll. et Mor. ex Steud.) Baill. | 24 | GG | Southeast Asia | Shade tolerance, adaptation to aerobic soil |

Table continued

**Table 1 continued.**

| Complex/species | 2n | Genome | Distribution | Useful or potentially useful traits |
|---|---|---|---|---|
| *O. ridleyi* complex | | | | |
| *O. longiglumis* Jansen | 48 | HHJJ | Irian Jaya, Indonesia, & Papua New Guinea | Resistance to blast and bacterial blight, shade tolerance |
| *O. ridleyi* Hook f. | 48 | HHJJ | South Asia | Resistance to stem borer, whorl maggot, blast, bacterial blight |
| Other complexes | | | | |
| *O. brachyantha* Chev. et Roehr. | 24 | FF | Africa | Resistance to yellow stem borer, leaffolder, and whorl maggot, tolerance of lateritic soil |
| *O. schlechteri* Pilger | 48 | ? | Papua New Guinea | Stoloniferous |
| *O. neocaledonica* Morat | 24 | ? | New Caledonia | ? |

was domesticated in parts of West Africa and remains locally important in some farming systems in those areas.

In the thousands of years of selection by farmers to meet their widely diverse needs and in the process of dispersal since domestication, rice has formed a tremendously broad range of genetic diversity as reflected in the large number of varieties existing today. *O. sativa* is estimated to have more than 140,000, including primitive varieties (landraces) and improved varieties (Jackson 1995). These make up an important component of the primary rice gene pool (Fig. 1), which is necessary for further improvement of rice cultivars. Harlan and de Wet (1971) define the primary gene pool as one containing races that usually belong to the same biological species as cultigens and that can yield reasonably fertile hybrids with the cultigens. Therefore, rescues in the primary gene pool can easily provide novel genetic variability to rice varieties through sexual hybridization.

A good overview of the genetic structure of the *Oryza* genus (AA genome) has been provided by extensive studies using various means: morphological studies, cytogenetics, interspecific hybridization, and biochemical and molecular markers. Most authors agree that *O. glaberrima* originated in West Africa from *O. barthii,* sometimes called *O. breviligulata* (Portères 1950, Oka 1974, Second 1982). Several hypotheses regarding the domestication of *O. sativa* have been debated (see Oka 1988 for a review). It was proposed that *O. sativa* was domesticated from the perennial type of common wild rice *O. rufipogon* (Sampath and Rao 1951, Sampath and Govindaswami 1958, Oka 1974) or from the annual common wild rice *O. nivara* (Chatterjee 1951, Chang 1976). But a diphyletic origin of *O. sativa* (Second 1982)—two independent domestications on each side of the Himalayan barrier from *O. nivara* populations—is the hypothesis found to be the most consistent with isozyme and DNA marker data (Glaszmann 1987,1988, Second 1982, 1991). This origin led to the actual structure of *O. sativa* in the two main subspecies, indica and japonica (Glaszmann 1987, 1988, Matsuo 1952, Oka 1974, 1988, Second 1982). Continuous hybridiza-

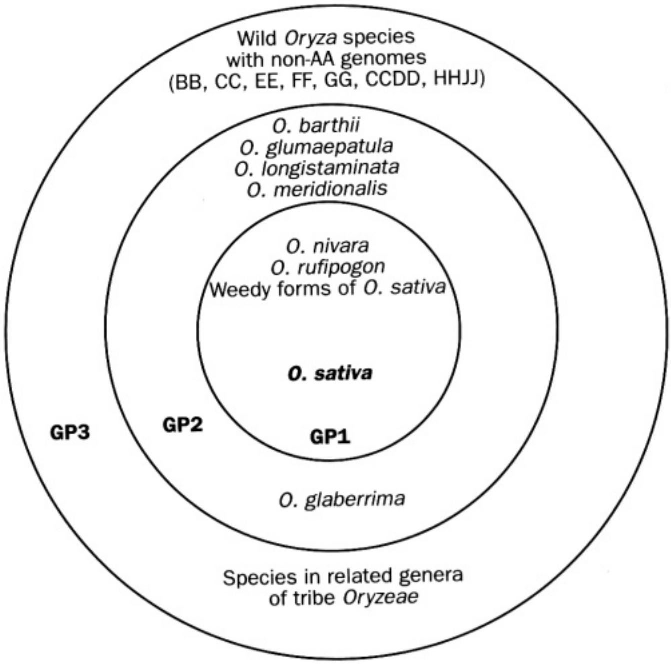



**Fig. 1.** The gene pool of the main cultivated rice species, *Oryza sativa.* The crop gene pool can be divided into primary (GP1), secondary (GP2), and tertiary (GP3) (Harlan and de Wet 1971). Species are categorized in these pools according to the feasibility of gene transfer from those species to the crop species (primary pool: easy, secondary pool: difficult, tertiary pool: very difficult; see text for more detailed definition). We have represented this classification for *O. sativa* only and not for the two cultivated species at the same time as is usually done (Harlan and de Wet 1971). This permits a better representation of *O. glaberrima.* A different diagram has to be drawn if *O. glaberrima* were considered the "central" crop species.

tions between these groups, along with introgression from wild relatives and the mutation process, have produced the actual genetic diversity of *O. sativa.*

The most useful classification of *O. sativa* has so far been provided by isozyme studies. Glaszmann (1987) was able to cluster *O. sativa* varieties into six groups. The two main groups, I and VI, correspond to the indica and japonica varieties, respectively. Because this classification is consistent with other biological criteria, it has been well accepted by plant breeders. But the isozyme-defined groups should not be seen as "independent." Although discriminant marker loci exist between these groups, a recent study has shown that indica and japonica varieties are not "pure." They are actually mosaics of both indica and japonica alleles (Second and Ghesquière 1995, Second et al 1995) and can be explained by the above hybridization process between indica and japonica varieties.

Apart from the cultivated rice species and their direct ancestors, more than a dozen other wild species in the genus *Oryza* are distributed throughout the tropics of

Asia, Africa, South and Central America, and Australia (Table 1). The wild species in *Oryza* contain different genomes and have different biosystematic relationships with cultivated rice. These can be categorized into either a secondary gene pool (containing races or species that are crossable with cultivated species; gene transfer to cultivated species is restricted) or tertiary gene pool (containing races or species that are difficult to cross with cultivated species; gene transfer to cultivated species is impossible without special genetic procedures). Assigning species depends on how close they are related to cultivated rice and with what difficulty the genes could be transferred from species in this gene pool to the cultivars (Fig. 1). There are also many species in the related genera of the tribe *Oryzeae* (Table 2). All of these are distantly related to the cultivated rice species and they belong to the tertiary gene pool of rice (Fig. 1).

## The need for biodiversity

Crop genetic diversity is the basis of our food supply and therefore the basis of our survival. This is true of an agricultural subsistence-based society or a market-integrated, technologically advanced one. Genetic diversity allows farmers and plant breeders to adapt a crop to heterogeneous and changing environments and to provide it with resistance to pests and diseases. Large areas planted to a single variety or a few cultivars with a similar genetic background can be especially vulnerable to pests, diseases, and severe weather (NRC 1993, Plucknett et al 1987, Wilkes 1989).

Rice, along with maize and wheat, is one of the three leading food crops in the world. It is the staple food and the principal crop in humid and subhumid Asia, where

**Table 2. Genera, number of species, chromosome number, distribution, and spikelet structure in the tribe *Oryzeae* (modified from Vaughan 1989).**

| Genus | Species (no.) | 2n = | Distribution | Spikelet structure |
|---|---|---|---|---|
| *Chikusiochloa* Koidz. | 3 | 24 | China & Japan; t[a] | Bisexual |
| *Hydrochloa* Beauv. | 1 | | USA & Mexico; t | |
| *Hygroryza* Nees | 1 | 24 | Asia; t + T | Bisexual |
| *Leersia* Sw. | 20 | 24 | Worldwide; t + T | |
| *Luziola* Juss. | 11 | 48, 60, 96 | N. & S. America; t + T | Bisexual |
| *Maltebrunia* Kunth | 5 | Unknown | Tropical & S. Africa; T | Unisexual |
| *Oryza* Linnaeus | 22 | 24, 48 | Pan-tropical; T | Bisexual |
| *Porteresia* Tateoka | 1 | 48 | South Asia; T | Bisexual |
| *Potamophila* R. Br. | 1 | 24 | Australia; t + T | Bisexual |
| *Prosphytochloa* Schweick | 1 | Unknown | South Africa; t | Unisexual & bisexual |
| *Rhynchoryza* Baill. | 1 | 24 | South America; t | Bisexual |
| *Zizania* Linnaeus | 4 | 30, 34 | Europe & Asia; North America; t+T | Bisexual |
| *Zizaniopsis* Doell ex Aschers. | 5 | 24 | North & S. America; t+T | Unisexual |

[a]T = tropical, t = temperate.

it accounts for 30–50% of agricultural incomes and provides 50–80% of the calories consumed by the people. In this region, recent projections estimate that production must increase to more than 800 million t over the next 30 yr, from the current 480 million t (Hossain 1995). Rice production has increased by 2.4% annually over the past 30 yr. This feat has been accomplished mainly through the widespread adoption of modern varieties (MVs) in irrigated land and large-scale public and private investment in infrastructure to convert rainfed areas to irrigation (Hossain 1995).

The development of new modern rice varieties has depended on the continued availability of genetic diversity (Chang 1984, Jackson and Huggan 1993). The main source of this diversity is the traditional varieties that have been grown and selected for generations by rice farmers of the world. All modern varieties can be traced back to landraces. The pedigree of IRRI varieties up to 1994 can be traced back to 40 landraces from 12 different countries (de Leon and Carpena 1995). Wild species also represent a rich pool of diversity, particularly for their ability to withstand pests and diseases (Jackson 1995). They have made an important contribution to rice improvement (Chang 1984). For example, a strain of *O. nivara* collected from Uttar Pradesh, India, has been the sole source of resistance to grassy stunt virus, and it has helped reduce the incidence of that disease on millions of hectares (Chang 1984). New biotechnology tools promise to increase the usefulness of genes of wild relatives for rice improvement (Khush et al 1994). In addition, wild rice species are useful in basic research. The first saturated restriction fragment length polymorphism (RFLP) genetic map of rice was developed using a cross between *O. sativa* and *O. longistaminata,* a wild species found in Africa (Causse et al 1994).

Although modern varieties have been widely adopted, particularly in irrigated areas, traditional varieties still play an important role in the livelihood of many rice farmers. Small rice farmers in Asia and Africa continue to grow thousands of different varieties for specific traits (such as aroma or cooking quality) or for particular agroecological adaptations.

Maintenance of genetic diversity at the farm level is important not only for small traditional farmers but also for technologically advanced farmers. A broad genetic diversity, genic and cytoplasmic, is essential to cope with production constraints and risks common to intensive cultivation and continuous monocropping. It is needed to slow down genetic changes in a major pathogen or insect pest, to prevent the evolution of a minor pest into a major one, to minimize yield reduction caused by unusual weather, to counterbalance the likelihood of an epidemic associated with the continuous planting of a major crop in the tropics and subtropics, and to provide the potential for further genetic improvement (Chang 1984, 1994).

## Threats to biodiversity

The widespread adoption of modern rice varieties, together with modern inputs such as fertilizers and pesticides, and the development of irrigation have contributed to an increased food supply and a decline in real rice prices (Hossain 1995). But these changes have also contributed to the loss of genetic diversity. This loss, also known as genetic erosion, has been recognized as a problem since the early 1960s. It has been more formally defined as the loss of genes from a gene pool attributed to the elimination of populations caused by factors such as the adoption of high-yielding varieties, farmers' increased integration into the market, land clearing, urbanization, and cultural change (Plucknett et al 1987, Brush 1991, 1995, Bellon 1996).

In Asia, populations of wild species become extinct because their natural habitat is endangered by the extension of cultivation areas or urban pressures. (During the Third Rice Genetics Symposium in 1995, Dr. H. Morishima [National Institute of Genetics, Japan] presented two photographs of the same location in Thailand. The first one showed a population of *O. rufipogon.* The second picture—taken a few years later—showed a gasoline station.) The consequences for genetic diversity at the species level are poorly known, however. It can be anticipated that the consequences are more severe for inbreeding species. A general observation is that the diversity of inbreeding species is mainly structured as a between-population diversity rather than a within-population diversity (Brown and Schoen 1992, Hamrick and Godt 1989). This means that the loss of an inbreeding population (compared with the loss of an outcrossing population) is more likely to be linked to the loss of a particular allele.

Chang (1984) estimated that more than 100,000 rice cultivars existed in Asia earlier in the 20th century. But with the advent of modern, high-yielding varieties and intensive cultivation, a small number of productive and relatively uniform cultivars now dominate commercial production (Chang 1994). (A similar genetic erosion—that did not initially involve modern varieties—occurred in West Africa when *O. sativa* was introduced. *O. sativa* tended to replace *O. glaberrima* because of its better overall agronomic value.)

As with other crops, rice scientists have been concerned that this reduction of genetic diversity on-farm may increase the vulnerability of rice to major disease or pest outbreaks (Chang 1984, 1994, Hargrove 1979, Hargrove et al 1980, Cuevas-Pérez et al 1992)[1]. This vulnerability may be enhanced by double-cropping large tracts of modern varieties in the tropics and subtropics (Chang 1994). For example, in Indonesia during the first crop of the 1992-93 season, four of the five popular varieties had IRRI material in their ancestry and two of them, IR36 and IR64, occupied 66% of the area planted to those five varieties (IRRI 1995). These two varieties have a coefficient of parentage of 0.289 (de Leon and Carpena 1995). For methodological

[1]In this part, we deal with two different aspects of variability that are often confounded. First, similar to the diversity indexes used in ecology, the genetic diversity of a set of individuals or varieties is a function of the number and frequency of alleles at a given number of genes in that set of varieties. Second, the genetic base of a variety is the set of its parents. The higher the genetic similarity of the parents, the narrower the genetic base. Growing a pure line that was bred from a large genetic base does not mean that a large genetic diversity is grown. If only one pure line is grown, the genetic diversity of the "set" of grown varieties is null, whatever the genetic base of this pure line.

reasons,[2] we should be cautious in interpreting these data, but they nonetheless illustrate the importance of genetically related material in the rice landscape.

Chang (1984) has suggested a link between pest outbreaks in rice-producing countries of Asia and the extent of the deployment of modern varieties (Chang 1984). He contrasted the situation during the early 1980s in parts of Indonesia and the Philippines, Sri Lanka, Taiwan, and Vietnam, where important and frequent epidemics occurred, with the situation in Thailand, Bangladesh, and Myanmar, which experienced only light pest outbreaks, and where a small proportion of the area was still planted to modern varieties. The movement toward genetic vulnerability, however, has not led to devastating yield losses on the scale of those experienced by the United States during the leaf blight epidemic in maize of 1970-71 (Chang 1984). A high proportion of plant breeding investment has been devoted to increasing the disease and pest resistance of modern varieties (Evenson and Gollin 1997). Since the late 1970s, newer rice varieties have resistances to six or seven major rice pests incorporated in them (Byerlee 1994). The early modern rice varieties have been completely replaced by new varieties with multiple pest and disease resistance (Otsuka et al 1994).

Evidence suggests that some modern varieties have a narrow genetic background. For example, Lin (1991) has shown a narrow genetic background of japonica varieties released in Taiwan between 1940 and 1987. A similar pattern was documented for U.S. rice cultivars (Dilday 1990). There were also concerns about the narrow genetic diversity present among IRRI varieties (Chang 1994, Hargrove 1979, Hargrove et al 1980). For example, all semidwarf cultivars share the *sd1* gene for short plant stature. Most semidwarf cultivars derived from IR8 and other early IRRI releases carry the cytoplasm of Cina (Tjina). All indica-type rice hybrids in China share the *sd1* gene and the wild abortive (WA) source of cytoplasmic male sterility (CMS) (Chang 1994).

Although valid, these concerns should be qualified, and we should separate biotic from abiotic constraints. An abiotic constraint is not susceptible to breakdown so there is no inherent danger in having the same gene in all varieties (e.g., *sd1* for plant

---

[2] The use of coefficient of parentage as an indicator of genetic diversity merits a comment. The coefficient of parentage between varieties is based only on the pedigree origin of a variety—the coefficient increases if the varieties share common genitors. Although this coefficient is convenient because it is relatively easy to calculate, its computation is often based on assumptions known to be wrong. First, traditional varieties are supposed to be unrelated. As explained above, although O. sativa is divided into two subspecies, japonica and indica varieties share part of their genome (and alleles) (Second and Ghesquiere 1995). Second, it is assumed that each parent contributes half of the genome to the progeny. This is not always true in rice, particularly in indica/japonica crosses (Oka 1953, Pham 1991, Pham et al 1990). For example, in the 281 single-seed-descent lines derived without selection from the indica/japonica cross CO 39/ Moroberekan, 14 lines were found to have only two RFLP alleles from Moroberekan versus 125 from CO 39 (Wang et al 1994). Coefficient of parentage is therefore not reliable and should be used only as a first approximation. Similarly, the number of landraces involved in the parentage does not mean much; it depends on how much they are related. In rice, using molecular markers to assess genetic similarity between parental lines is preferred. Though still imperfect, molecular markers are generally better means to assess real genetic diversty, because they are "neutral" in terms of adaptation.

height), except when this gene is physically linked (on the same chromosome) to genes controlling biotic constraints. For biotic constraints, more attention should be paid to diversity of genes for resistance to pests and diseases than to genetic background because of breakdown problems. Breeders have to define a twofold strategy: What resistance genes should be introduced in the varieties? How should these varieties be released in time and space? (See Mundt [1994] for a review.) The diversity of the host cannot be separated from the diversity of the pathogens. For example, in blast (caused by *Magnaporthe grisea;* Barr 1997), the ability of the pathogen to vary is tremendous, and a major gene will break down in 1–2 yr in some areas. But there are more stable pathogens for which major genes can remain efficient for a longer time and for which diversity is not that much of an issue. The "usefulness" of genes should be weighed accordingly (B. Courtois, IRRI, personal communication). The lack of cytoplasmic diversity can be easily corrected. It is necessary to pay attention to the direction of the crosses (using a parent as male rather than as female). The serious problem is for hybrid rice, because in this case the cytoplasm is interacting with a nuclear gene and this interaction creates the male sterility necessary for seed production and it is nearly impossible to change the cytoplasm. Breeders are aware of this problem and are working to address it.

IRRI scientists have been sensitive to the need to increase genetic diversity in their breeding programs, and therefore ultimately on-farm. For example, a recent study of the pedigrees of IR varieties and their relationships indicates a deliberate attempt to broaden the genetic base of IR varieties in particular and of Philippine rice varieties in general by having at least one new donor variety in the pedigree of new cultivars being released (de Leon and Carpena 1995). Evidence suggests that the number of landraces incorporated in the new varieties released has increased over time. The genetic relationship among varieties bred at IRRI is declining (de Leon 1994). Evenson and Collin (1997) present evidence that the number of landraces incorporated in IRRI lines has steadily risen from the early 1960s to the early 1990s. They note that an impressive number of new landraces, as well as one or two wild species, have been introduced into the pool of successful varieties.

Going beyond this simple census of varieties used in IRRI breeding schemes, studies using molecular tools have to be undertaken to assess the actual genetic base of IRRI varieties and the genetic diversity resulting from their frequent occurrence in farmers' fields.

Recent developments in rice genetics bring new concerns and new hopes. Specific concerns about the use of genetic transformation have been raised (Clegg et al 1993, Kareiva et al 1994). In terms of biodiversity, the main concern is the potentially harmful effect of the escape of alien genes from genetically engineered cultivars to populations of wild species. For example, apomixis, if introduced in wild outcrossing populations, could threaten sexual reproduction in these populations. But these are theoretical scenarios. Rice scientists are extremely conscious about the release of transgenic cultivars (IRRI 1996a). Studies on the potential impact on wild rice of the escape of the *Bt* gene from "*Bt* rice" have been undertaken by IRRI. ("*Bt* rice" is rice that has been modified by means of biotechnology, with genes from *Bacillus thuringiensis* to produce toxins for resistance to insects [IRRI 1996a].) They follow the safety regulations developed by the National Committee on Biosafety of the Philippines (IRRI 1996a). A "gene-proof" greenhouse that prevents the release of pollen from transgenic plants to the environment was built at IRRI to carry out experiments involving transgenic plants (IRRI 1996a).

On the other hand, it is obvious that breeding for the "new plant type" (Peng et al 1994) will induce a drastic change. The genetic base of the new plant type lies in tropical japonica varieties in contrast to indica varieties, which are the base of current improved varieties.

Breeders will have more work to do with traits under polygenic control—an issue that genetic engineering will not be able to address for several years—particularly traits involved in abiotic constraints (e.g., salinity tolerance, drought tolerance) and in resistance based on several minor genes. Changes in methods (recurrent selection, marker-assisted selection) will permit a more efficient breeding program for these traits. At the same time, these methods will promote wider use of the diversity involved in crosses.

Rice is grown under very different conditions. Four major ecosystems have been recognized (Khush 1984): irrigated, rainfed lowland, upland, and flood-prone. Although genetic erosion has definitely occurred in rice, detailed knowledge of the levels of genetic erosion in the different rice ecosystems is scarce. Data on the genetic diversity present in each of these ecosystems prior to the introduction of modern varieties are lacking. The adoption of modern varieties has been uneven among rice ecosystems (Byerlee 1994, Dalrymple 1986). The common view is that the highest rate of adoption occurred in the irrigated ecosystem, with a more limited impact on the rainfed lowland ecosystem and a very low adoption in the upland and flood-prone ecosystems (Byerlee 1994, Chang 1994, IRRI 1992, 1993, 1994). If a direct relationship between degree of adoption of modern varieties and level of genetic erosion can be construed, then the highest genetic erosion should have taken place in the irrigated ecosystem and the lowest in the upland and flood-prone ecosystems.

Threats to rice genetic diversity are related not only to the adoption of modern varieties but also to the loss of farming systems where some of this diversity has evolved. For example, in the upland ecosystem, the loss of genetic diversity may be more related to the shift from rice to other crops such as maize and vegetables. There is no question of the trend to move away from rice in upland areas (Pandey 1996). In the flood-prone environment, drainage and other infrastructure development and the conversion to an irrigated ecosystem may have an impact on the loss of habitat where adapted traditional varieties have thrived.

Although traditional varieties are a repository of genetic diversity and their loss has important implications for its conservation, we should not assume that maintaining genetic diversity on-farm is just a question of planting only traditional varieties. On the one hand, planting only one or two traditional varieties over large areas may be the same as having the same number of modern varieties. Furthermore, several traditional varieties may be genetically similar; in this case, even planting many varieties may not indicate a large level of genetic diversity in an area. On the other hand, the adoption of modern varieties does not automatically lead to a complete displacement of traditional varieties, and both can coexist in the same farming system (Bellon 1991, Brush 1991, Dennis 1987, Louette et al 1997). In fact, this coexistence can be translated into an increased level of genetic diversity in an agroecosystem (Dennis 1987) and can promote evolutionary changes in traditional varieties. Understanding and documenting the changes in genetic diversity in a rice ecosystem, or any other agroecosystem, are not simple and require the collaborative work of geneticists and social scientists (Bellon et al 1997, Brush 1995). Genetic erosion is a much more complex process than originally thought (Brush 1995). An ongoing research program by IRRI scientists on farmers' management of rice diversity is addressing these issues (Pham et al 1996).

## Conservation strategies

The need to conserve the diversity of the rice gene pool has been recognized as important for many decades, particularly given that genetic erosion has occurred and continues to take place. Depending on the objectives and scopes of the activity, there are two basic approaches to rice genetic resources conservation: *ex situ* and *in situ* conservation.

### *Ex situ* conservation

*Ex situ* conservation includes activities of collecting seed samples of cultivated or wild species from the original sites and then storing the samples in genebanks. This conservation has so far been the principal strategy for preserving crop genetic resources. For rice, this method has been favored because of seed biology. Rice has so-called orthodox seeds that can be dried to a relatively low moisture content (6%) and stored at subzero temperatures. Under these conditions, the viability of rice seeds can be maintained for long periods. Through the storage of seeds in a genebank, their longevity is assured via the provision of conditions that reduce to a low level the decline in seed viability and the decay of variability of the stored samples. *Ex situ* conservation is a safe and efficient way of conserving rice genetic resources and has the advantage of making the germplasm readily available for use by breeders and for study by researchers (Jackson 1995).

Since the early 1960s, IRRI, in collaboration with national scientists, has played an important role in the collection, conservation, characterization, evaluation, and distribution of rice varieties and wild species, especially in Asia, and has been a catalyst for genetic resources activities in national programs. The rice germplasm collection conserved in the International Rice Genebank (IRG) at IRRI has global importance. It comprises more than 80,000 accessions of cultivated rice and wild species. More than 76,000 of these accessions belong to *O. sativa,* 1,250 accessions are *O. glaberrima,* and nearly 3,000 accessions are wild species. Collection efforts focus on countries in which rice diversity is underrepresented in the collection and is threatened by changes in rice cultivation. Lao PDR is a good example. During 1995, about 2,000 samples of cultivated rice were collected (Appa Rao et al 1997). One set of germplasm collected has been conserved at the National Agricultural Research Center near Vientiane. Another set has been sent to IRRI for safety duplicate conservation.

The Base Collection of the IRG has a capacity of more than 120,000 accessions of rice, stored at -20 °C in vacuum-sealed aluminum cans. with two cans (±120 g) per accession. In the Active Collection, from which germplasm is exchanged with researchers worldwide, rice seeds are stored in hermetically sealed aluminum foil packets, containing approximately 400–500 g of seeds. Separate 10-g packets are ready for immediate exchange. Safety duplicate storage of the IRRI collection in sealed boxes is undertaken at the National Seed Storage Laboratory (NSSL) in the -20 °C vaults at Fort Collins, Colorado, USA. The germplasm stored at NSSL, however, does not become part of the USDA collection.

The rice genetic resources maintained in the genebank at IRRI are held in trust for the world community (see "Policy issues" later in this chapter). More than 43,000 samples were distributed outside IRRI between 1991 and 1995, including more than 17,000 sent to national research institutions in developing countries. Jackson (1995) reports a notable example of the importance of *ex situ* collections for on-farm diversity. Cambodian farmers were discouraged from growing deepwater rice varieties during the period of civil strife. When the political environment changed and allowed farmers to grow them again, these varieties had already been lost. But because a set of germplasm was conserved in the IRRI genebank, the return of these varieties to Cambodian farmers was made possible.

The global exchange of rice germplasm is also facilitated by the International Network for Genetic Evaluation of Rice (INGER). (INGER was formerly called the International Rice Testing Program.) Since 1975, INGER has distributed more than 19,000 nursery sets to more than 60 countries (Jackson 1995).

Some wild species cannot be collected as seeds (e.g.. *O. schlechteri, Zizaniopsis*) or few seeds can be collected (as in the perennial *O. rufipogon).* In those cases, collectors take vegetative parts of the plants as samples. At IRRI, the individual wild plants are grown in a special screenhouse to produce seeds. As long as no seeds are produced—e.g., for *O. schlechteri, Leersia hexandra, Zizaniopsis,* and *Potamophila* genera—plants are maintained in a living collection. This living collection can also be used for characterization and research purposes.

*Ex situ* conservation also promotes the use of stored accessions by providing basic information about them. The International Rice Genebank Collection Information System (IRGCIS) stores information related to accession identification, passport data, morphoagronomic characterization, and germplasm evaluation and use. Besides "classical" traits such as tolerance for biotic and abiotic stresses, isozyme and DNA marker data are important in germplasm evaluation. The former provides valuable information on the classification of *O. sativa* accessions within the diversity at the species level. Several thousand accessions have been evaluated for isozyme markers.

DNA markers such as random amplified polymorphic DNA (RAPDs) are promising tools for identifying duplicate accessions (Virk et al 1995) and even predicting values of morpho-phenological traits (Virk et al 1996). In poorly known wild species, DNA markers are of interest in identifying the species and their biosystematic relationships (Vaughan 1989, Second 1991).

Seeds placed under *ex situ* conservation in a genebank become isolated from the environment where they originated. In evolutionary terms, *ex situ* conservation is static. Concerns have been raised regarding the observation that static conservation may decrease the adaptive potential of crops and wild species populations in the future. Thus, *ex situ* conservation cannot be considered as the only approach for conserving genetic diversity of the rice gene pool. Complementary "dynamic" approaches, briefly described below, are also necessary.

## *In situ* conservation of wild species

In contrast to *ex situ* conservation, *in situ* conservation of wild species aims to preserve species or populations in their original habitats. This is the area of rice genetic resources that has undoubtedly received the least attention. Jackson (1995) remarked that, despite developments in rice genetics, surprisingly limited scientific input has passed into *in situ* conservation and the design and management of genetic reserves. Just 10 species of wild rice have been reported from 18 reserves in Africa and South and Southeast Asia (Vaughan and Chang 1992). We therefore present issues that *in situ* conservation of wild rice should address after clarifying the taxonomy of the wild species of rice. Biosystematic research is essential for providing basic information on the characteristics of the species to be conserved.

According to Frankel et al (1999, *in situ* conservation should meet three criteria: survival of the species/population; maintenance of the evolutionary potential and, for wild relatives, of the primary gene pool; and development of new genotypes.

*Survival of the species/population and maintenance of evolutionary potential.* We must know whether some rice species are endangered at the species level, because rare and locally distributed species (such as *O. australiensis* and *O. longiglumis*) might be threatened. Widely distributed species (such as *O. rufipogon, O. nivara,* and *O. oficinalis*) are more likely to be threatened as populations. Taking a census of existing populations would be a useful step. The demographic and genetic risks that the populations face are known theoretically (Frankel et al 1995). *In situ* conservation should allow populations to continue their evolution within the natural environment (Ford-Lloyd and Jackson 1986). A description of the genetic diversity of wild species and of its structure is required. *Ex situ* conservation, although important for the long-term survival of the wild species, should always be seen as a potential emergency solution. At the same time, *ex situ* conservation permits scientific study relevant to conservation and use. Because they are part of our environment, however, *in situ* wild populations have intrinsic value—what economists call "existence value." Their conservation might not be possible without action at a higher level (ecosystem, plant community reserves). Characterization of the threats, if any, as well as the definition of conservation actions address biological, social, and political issues. Characterization will require research involving disciplines such as botany, taxonomy, ecology, population and molecular genetics, land management, geographic information systems, anthropology, and economics.

*Development of new genotypes.* It might be of interest to study the *in situ* conservation of populations of the annual *O. rufipogon* and *O. nivara* that grow close to cultivated *O. sativa* because they could exchange genes. Spontaneous hybrids between wild and cultivated species have been observed by several authors (Morishima et al 1980; Lu, personal communication). Mutual introgression is likely (Second 1991). Locations where wild species grow naturally would be excellent sites for laboratories in which to study the potential benefits of *in situ* gene flow within the primary gene pool. In addition, useful data on the risk of escape of transgenes from cultivated to wild species would be provided.

## On-farm conservation

This type of *in situ* conservation of cultivars is increasingly being considered by some scientists, nongovernment organization representatives, farmers, and international institutions as an important complement to *ex situ* conservation (Altieri and Menick 1987, Brush 1991, IPGRI 1993, Oldfield and Alcorn 1987). On-farm conservation can be defined as the continued cultivation and management of a diverse set of crop populations by farmers in the agroecosystems where a crop has evolved. This set may include the weedy and wild relatives of the crop that may be present together with it and, in many instances, tolerated (Bellon et al 1997). On-farm conservation is based on the recognition that, historically, farmers have developed and nurtured crop genetic diversity, and that this process continues in spite of socioeconomic and technological changes. It emphasizes the role of farmers for two reasons: (1) crops are not only the result of natural factors, such as mutation and natural selection, but also and particularly of human selection and management; and (2) in the last instance, farmers' decisions determine whether these populations are maintained.

On-farm conservation of local varieties is an existing strategy for food security. It is also a potential strategy for genetic conservation. By its very nature, on-farm conservation is dynamic because the varieties that farmers manage continue to evolve in response to natural and human selection. In this way, it is believed that crop populations retain an adaptive potential for the future (Bellon et al 1997, Jackson 1995). But little is known about the relationship between the number of varieties that farmers maintain and the kind of management given to them, the actual genetic diversity present in their agroecosystems, and the evolutionary changes that may occur. IRRI is currently undertaking research to address these issues (Pham et al 1996). On-farm conservation, which may also include management of experimental composite populations (Pham et al 1994, Bellon et al 1997), has to be seen as one of the components of a global approach to conserving rice genetic resources that involves both static and dynamic methods.

## Use: farmers' perspectives

Rice farmers in Asia have grown and continue to grow, in many places, many varieties (Bellon et al 1997, Chang 1984, Lando and Mak 1994a,b,c). Planting several rice varieties simultaneously—rice infraspecific diversity—can be seen as an adaptation, a way of attaining goals and solving problems. This practice has provided farmers throughout history, until today and in many parts of the world, with numerous goods and services, both for production and consumption, including ritual and religious purposes (Bellon 1996). This practice fulfills different roles for farmers' well-being, which much of the time are complementary rather than mutually exclusive. Table 3 presents some of the problems and goals that rice infraspecific diversity addresses, as well as some examples.

**Table 3. Functions of rice infraspecific diversity for farmers.**

| Functions | Examples |
|---|---|
| To farm in a variety of environments characterized by different soil qualities, temperature and rainfall regimes, topographies, etc. | Many rice farmers match different varieties to different field levels, which in turn reflect different regimes of water availability (Lambert 1985, Lando and Mak 1994a,b,c). |
| To cope with production risks and uncertainty, such as rainfall variability | In Uttar Pradesh, India, a popular variety, called gora, which is a mixture of brown, black, and straw genotypes that differ in drought resistance and grain quality, is used to cope with rainfall variability (Vaughan and Chang 1992). |
| To cope with different pests and pathogens | Farmers in an Indian rainfed village perceived that traditional varieties are more resistant to pests and diseases than modern varieties (Kshirsagar and Pandey 1996). |
| To avoid or minimize labor bottlenecks | Farmers in Asia and Africa plant varieties with different maturities to spread labor during the growing season (Conklin 1957, Richards 1986). |
| To fit different budget constraints | Farmers in an Indian rainfed village perceived that modern cultivars required more intensive management in terms of fertilizers and timely farm operations than traditional varieties (Kshirsagar and Pandey 1996). |
| To provide variety for a monotonous diet | Some farmers in the Philippines mix glutinous and nonglutinous varieties to get improved texture. |
| To provide special uses | Farmers in Vietnam prepare special cakes with rice for the Tet festival. |
| To fulfill rituals, generate prestige, forge social ties | The Iban of Sarawak, an ethnic group in Malaysia, locate a special ritual segment in the middle of a field where a special rice variety is planted (Sutlive 1978). |

Market integration and the availability of new technologies can change dramatically the adaptive value of rice infraspecific diversity. They provide new ways of solving problems, create new goals and new problems, and make others irrelevant; in the process, they decrease the value of maintaining rice infraspecific diversity, which translates into its loss. Even under conditions of market integration and availability of new technologies, however, maintaining rice diversity on-farm may still be advantageous. In developing nations, market imperfections (Brush et al 1992, de Janvry et al 1991, Plattner 1989), which limit the ability of farmers to substitute diversity through the market, are very common (Brush et al 1992). Furthermore, poor farmers may lack the income necessary to purchase these substitutes. We are increasingly aware that plant breeding efforts have not benefited all farmers, particularly the small and poor ones in marginal areas (Lipton and Longhurst 1989). We need to broaden the scope of plant breeding strategies and redefine priorities to increase the compatibility between development and diversity (Cooper et al 1992, Sperling et al 1993).

Farmer participatory breeding is emerging as a way to link formal breeding to the needs of small farmers in marginal environments (Eyzaguirre and Iwanaga 1995, Sperling and Loevinsohn 1995). It consists of involving farmers in the early stages of selection among either existing finished varieties or segregating material from crosses (Sperling and Loevinsohn 1995). Rice has been the focus of most breeding efforts (Maurya et al 1988, Witcombe and Joshi 1995). The work of IRRI plant breeders in the rainfed lowland ecosystem attempts to generate large and diversified sets of breeding materials that can cover different target environments (Sarkarung 1995). Farmer participatory breeding methods strive to increase the choice of materials for farmers and therefore enhance the value of genetic diversity to them.

## Use: breeders' perspectives

The main concern of breeders is to develop varieties with a wider genetic base and with increased productivity, yield stability, and sustainability over a range of environments. Cultivation of such varieties will minimize losses in yield caused by diseases, insects, and unfavorable climatic conditions. Moreover, growing these varieties will reduce the use of pesticides, help maintain safer environments, and allow cultivation of these varieties in marginal lands. The success of any plant breeding program depends on the availability of genetic variability for a range of agronomic traits. The major sources of genetic diversity in rice are

- the cultivated *O. sativa* gene pool consisting of primitive cultivars, landraces, and improved high-yielding varieties;
- wild species of *Oryza* and related species and genera comprising the primary, secondary, and tertiary gene pool;
- induced mutants—obtained through physical and chemical mutagenesis;
- somaclonal variants—obtained through tissue and cell culture procedures; and
- transgenic plants—novel sources.

Precise knowledge of genetic diversity is essential for using genetic resources and widening the gene pool of rice cultivars. Various techniques are available for classifying germplasm—e.g., those based on morphological and physiological traits, isozyme and restriction fragment length polymorphism (RFLP), RAPD, amplicon length polymorphism (ALP), polymerase chain reaction (PCR)-based RFLPs, and microsatellites (Ghareyazie et al 1995, Glaszmann 1987, Wang and Tanksley 1989, Wu and Tanksley 1993, Yu and Nguyen 1994). Recent advances in biotechnology approaches such as somaclonal variation, protoplast fusion, embryo rescue, molecular markers, and DNA transformation have opened new avenues for increasing genetic diversity for various traits in commercial cultivars. Genetic diversity in rice cultivars has increased more than ever with advances in cell culture, chromosomal manipulation, marker-aided selection, genetic engineering, the use of the *O. sativa* gene pool and related wild species germplasm, and novel sources of diversity from biological systems of plants and microorganisms.

## Widening the gene pool of rice cultivars

The *O. sativa* gene pool is a rich source of genetic diversity. Rice scientists have successfully exploited this germplasm in developing improved rice cultivars grown worldwide. In several cases, however, useful variability in rice germplasm is limited or lacking. Under such situations, wild species (which are an important reservoir of useful genes for resistance to major diseases and insects, tolerance for abiotic stresses, and diversification of cytoplasmic male sterility sources) (Table 1) offer great potential to widen the gene pool of rice. *O. rufipogon* was even identified as a source of genes capable of improving yield (Xiao et al 1996). But several incompatibility barriers such as hybrid inviability, hybrid sterility, and hybrid breakdown operating at different levels limit the transfer of genes from wild species into commercial cultivars (Brar and Khush 1986, Khush and Brar 1992, Sitch 1990). Factors such as genomic disharmony, unfavorable gene interactions, chromosome instability, undesirable linkages, and lack of recombination further slow down the transfer of useful genes from wild species into crop plants. Approaches such as embryo rescue, protoplast fusion, and chromosome manipulations have been used to overcome some of these barriers. Isozyme, RFLP, and *in situ* hybridization techniques have facilitated the monitoring and characterization of introgression of alien genetic variation from wild species into cultivated varieties. Genetic engineering techniques have enabled the transfer of novel genes into rice cultivars from diverse systems, a procedure not possible before.

To broaden the gene pool of rice, we have produced a series of hybrids between *O. sativa* and wild accessions with the AA genome from the primary gene pool through direct crosses and between rice and various other wild *Oryza* species belonging to the secondary gene pool through embryo rescue (Brar and Khush 1995). Jena (1994) and Brar et al (1997) produced hybrids between rice and the tertiary gene pool through embryo rescue (*O. sativa* + *P. coarctata*). Researchers at the University of Nottingham, UK, produced hybrids among tertiary gene pool species through protoplast fusion. These hybrids have been produced to increase the genetic diversity in rice varieties. Hybrids between rice and wild species with the AA genome are produced through direct crosses without using embryo rescue. The $F_1$ hybrids involving rice and wild species other than those with the AA genome are completely male sterile and are backcrossed to the respective recurrent rice parents. Progenies are advanced through embryo rescue in subsequent backcrosses until fertile plants with 2n = 24 and 2n = 25 chromosomes become available. Plants with 2n = 25, referred to as monosomic alien addition lines (MAAL), have the normal chromosome complement of rice and one chromosome from the wild species. Fertile backcross progenies are evaluated for transfer of useful traits. Introgression lines carrying useful genes from wild species are identified and used in breeding programs.

## Increasing the genetic diversity of rice cultivars for resistance to diseases and insects

Several biotic and abiotic stresses reduce rice productivity and sustainability. To overcome these problems, a wider genetic base of cultivars with increased diversity is essential.

The rice crop has become more vulnerable to attack because of intensive cultivation, year-round favorable climate, better management practices, and reduced genetic variability of the cultivated varieties. A number of diseases and insects cause yield losses. Of these diseases, blast, sheath blight, bacterial blight, tungro, and grassy stunt are prevalent; among insects, brown planthopper, green leafhopper, whitebacked planthopper, stem borer, and gall midge commonly occur in most countries of tropical and subtropical Asia. Developing varieties with multiple disease and insect resistances is essential to enhance productivity and yield stability and also to minimize the use of pesticides. In the past, rice breeders have successfully identified the source of resistance in cultivated rice germplasm and have incorporated genes for resistance through conventional hybridization into numerous commercial cultivars grown worldwide. In some cases, however, variability useful for resistance is limited or lacking in the rice gene pool. Notable examples include resistance to sheath blight, yellow stem borer, tungro, and grassy stunt virus. Also, breeders need to incorporate genes from diverse sources; for this purpose, the wild species of *Oryza* are an important source for incorporating genetic diversity into commercial cultivars. A number of useful genes have already been transferred from wild species into rice (Table 4).

One of the first successful stories is the transfer of resistance to grassy stunt virus from the wild species *O. nivara* (AA genome) to rice (Khush 1977). In the late 1960s, grassy stunt was a major disease attacking rice. A large number of varieties were screened at IRRI for their reaction to grassy stunt under field conditions. Of 6,723 accessions of cultivated rice and several wild species of *Oryza,* evaluated using the mass screening technique, only one accession of *O. nivara* (accession 101508) was found to be highly resistant (Ling et al 1970). A backcrossing program began in 1969 using IR8, IR20, and IR24 as recurrent parents and *O. nivara* as a donor parent. By the late 1970s, grassy stunt-resistant lines that resembled IR8, IR20, and IR24 were obtained. Since then, grassy stunt resistance has been incorporated into several rice cultivars that are grown in many rice-growing countries. The first grassy stunt-resis-

**Table 4. Some examples of the use of the primary and secondary gene pools of *Oryza* for increasing the genetic diversity of cultivated rice.**

| Trait transferred to *O. sativa* (AA genome) | Donor *Oryza* species | | |
|---|---|---|---|
| | Wild species | Genome number | Accession |
| Grassy stunt resistance | *O. nivara* | AA | 101508 |
| Bacterial blight resistance | *O. longistaminata* | AA | – |
| | *O. officinalis* | CC | 100896 |
| | *O. minuta* | BBCC | 101141 |
| | *O. latifolia* | CCDD | 100914 |
| | *O. australiensis* | EE | 100882 |
| | *O. brachyantha* | FF | 101232 |
| Blast resistance | *O. minuta* | BBCC | 101141 |
| Brown planthopper resistance | *O. officinalis* | CC | 100896 |
| | *O. minuta* | BBCC | 101141 |
| | *O. latifolia* | CCDD | 100914 |
| | *O. australiensis* | EE | 100882 |
| | *O. granulata* [a] | GG | 100879 |
| Whitebacked planthopper resistance | *O. officinalis* | CC | 100896 |
| Yellow stem borer resistance | *O. brachyantha* [a] | FF | 101232 |
| | *O. ridleyi* [b] | HHJJ | 100821 |
| Sheath blight resistance | *O. minuta* [a] | BBCC | 101141 |
| Tungro tolerance | *O. rufipogon* [a] | AA | 105908 |
| | *O. officinalis* [b] | CC | 105220 |
| Increased elongation ability | *O. rufipogon* [a] | AA | CB751 |
| Tolerance of acid sulfate soils | *O. rufipogon* [a] | AA | 106412 |
| | *O. rufipogon* [a] | AA | 106423 |
| Cytoplasmic male sterility | *O. sativa* f. *spontanea* | AA | – |
| | *O. nivara* | AA | 104823 |
| | *O. glumaepatula* | AA | 100969 |

[a]Material under test. [b]Advanced backcross progenies being produced.

tant varieties—IR28, IR29, and IR30—were released in 1974; IR32 and IR34 were released in 1975; IR36 and IR38 in 1976; IR40 and IR42 in 1977 (Khush et al 1977); and IR48, IR50, IR52, IR54, IR56, IR58, and IR60 in subsequent years (Khush 1989).

Bacterial blight is another major disease that causes large losses to the rice crop in several Asian countries. Through conventional breeding, many varieties resistant to bacterial blight have been developed; they are now widely grown in Asia and serve as parents in numerous crosses at IRRI and in national programs. Bacterial blight-resistant IR20 and IR22 were released in 1969. Since then, several other resistant varieties have been released using genes for resistance from the *O. sativa* gene pool. So far, 20 genes have been identified for bacterial blight resistance in cultivated rice germplasm; of these, *Xa4, xa5,* and *Xa7* have been incorporated in most high-yielding cultivars.

A new gene, *Xa21,* with a wide spectrum of resistance to all six races found in the Philippines, has been transferred from the diploid wild species *O. longistaminata* (2n = 24 AA) through backcrossing (Khush et al 1990). *Xa21* has also been tagged with molecular markers (Ronald and Tanksley 1991). This gene is being incorporated into the new plant type rice through PCR-based molecular marker-aided selection. *Xa21* is used in the gene pyramiding program to develop durable resistance to bacterial blight. In addition, genes for bacterial blight resistance have also been transferred into rice from five other wild species (Table 4) across crossability barriers: from *O. officinalis* (2n = 24 CC) (Jena and Khush 1990), *O. minuta* (2n = 48 BBCC) (Amante-Bordeos et al 1992), *O. australiensis* (2n = 24 EE) (Multani et al 1994), *O. brachyantha* (2n = 24 FF) (Brar et al 1996), and *O. latifolia* (D.S. Multani, unpublished). The transfer of such genes from wild species has further increased genetic diversity for bacterial blight resistance of rice varieties.

Blast is another major fungal disease occurring throughout rice-growing countries. Besides useful genes that are incorporated from the *O. sativa* gene pool through conventional breeding, a new gene (*Pi9t*) has been transferred from *O. minuta* into elite breeding lines of rice (Amante-Bordeos et al 1992). The donors for tungro tolerance have been identified in *O. rufipogon* and the donors for resistance to sheath blight were found in *O. minuta.* Progenies generated from these crosses are being evaluated (Table 4).

A large number of donors for resistance to major insects have been identified in the primary *O. sativa* gene pool. So far, nine genes for resistance to brown planthopper, eight for green leafhopper, five for whitebacked planthopper, and four for gall midge have been identified in cultivated rice germplasm. Resistance to stem borers is polygenic in nature and none of the donors has a high level of resistance. These sources have been used in conventional breeding to develop numerous insect-resistant varieties. These multiple disease- and insect-resistant varieties are grown worldwide and have greater yield stability, thus contributing to greater food security. As an example, IR36, which is resistant to brown planthopper, green leafhopper, yellow stem borer, striped stem borer, and gall midge, was planted on more than 10 million ha around the world annually (IRRI 1982). Its cultivation alone provided an additional income of US$1 billion annually to rice growers and processors.

Besides the *O. sativa* gene pool, genes for resistance to brown planthopper have been transferred into an elite breeding line of rice from four wild species: *O. oficinalis, O. minuta, O. latifolia,* and *O. australiensis.* Lines developed from *O. sativa/O. officinalis* were found to be resistant to all three brown planthopper biotypes in the Philippines and they also showed resistance to biotypes from India, Bangladesh (Jena and Khush 1990), and Vietnam. In the Mekong Delta of Vietnam, IR36, IR42, IR2307-247, and IR13240-108 were introduced and widely grown from 1978 to 1990. These varieties became susceptible to brown planthopper in 1990. During 1991 and 1992, 168 lines from the second backcross of *O. officinalis* to IR31917-45-3-2, an IRRI breeding line, were tested for resistance to brown planthopper. Tests in Vietnam showed that many of these lines were also resistant to the new brown planthopper biotype in Vietnam. Four of these lines have been released as varieties in Vietnam: IR54751-2-44-15-24-3 was named MTL 98, IR54751-2-34-10-6-2 became MTL 103, IR54751-2-41-10-5-1 became MTL 105, and IR54742-23-19-16-10-3 became MTL 110.

We are identifying whether the genes for brown planthopper resistance that were transferred from the four wild species are new genes and are different from those genes already present in the *O. sativa* gene pool. One of the brown planthopper resistance genes transferred from *O. australiensis* has been tagged with a molecular marker (Ishii et al 1994). The gene is linked with molecular marker RG457 of chromosome 12 at a distance of 3.68 ± 1.29 centiMorgans. Such a close linkage is useful in marker-aided selection to transfer brown planthopper resistance from introgression lines into other elite breeding lines.

The *O. sativa* gene pool has limited variability in tolerance of yellow stem borer and sheath blight, two serious pests of rice. The two wild species, *O. brachyantha* (2n = 24 FF) and *O. minuta* (2n = 48 BBCC), possess a relatively higher level of resistance. Advanced backcross progenies produced through the embryo rescue technique are being evaluated for tolerance of these pests (Table 4). In addition, genetic engineering techniques have enabled the widening of genetic diversity for resistance to stem borer and sheath blight. Lin et al (1995) transferred the chitinase gene into rice and the resulting transgenic plants were found to have increased resistance to sheath blight.

A truncated endotoxin gene, *crylA(b)* from the bacterium *Bacillus thuringiensis (Bt),* was introduced into japonica rice cultivar Nipponbare through electroporation of protoplasts. Transgenic plants carrying the *Bt* gene showed a higher level of resistance to striped stem borer and leaffolder (Fujimoto et al 1993). Similarly, the introduction of the chitinase gene through transformation into rice has increased the genetic diversity of sheath blight resistance. Hayakawa et al (1992) introduced the coat protein gene for rice stripe virus into rice. Transgenic plants showed increased tolerance of stripe virus. These examples demonstrate that novel genes can be transferred through genetic engineering into rice to enhance genetic diversity for insect and pest resistance.

Like genetic engineering, somaclonal variation is another tool available to breeders to enhance genetic diversity for resistance to major diseases and insect pests. Recently, through somaclonal variation, a rice variety has been released for commercial cultivation in Hungary (Heszky and Simon-Kiss 1992). A large number of calli were produced from anther culture and several somaclones were evaluated for useful traits. Of several dihaploid somaclones, superior ones were selected. One of them, DAMA, was released as a variety. It possesses an increased level of resistance to blast. Likewise, progenies of protoplast-regenerated plants were tested for various agronomic traits. Variety Hatsuyume has been released for cultivation in Japan (Ogura and Shimamoto 1991). This protoplast-derived variety is early maturing and has a short stature and stiff culm. These examples demonstrate that biotechnology offers great potential to widen the genetic diversity in rice cultivars.

## Increasing genetic diversity for tolerance of abiotic stresses

Several abiotic stresses, such as unfavorable temperature and adverse soil and water conditions, affect rice yields. Conventional plant breeding approaches have been used to enhance tolerance of these stresses. A number of varieties with moderate tolerance of these stresses have been developed by exploiting the variability from the *O. sativa* gene pool. But work on exploiting variability for abiotic stresses from wild species has been limited. We are now evaluating progenies derived from crosses between *O. sativa* and *O. rufipogon* for increased elongation ability to develop varieties suitable for deepwater conditions. Similarly, progenies derived from *O. sativa* and *O. rufipogon* are being evaluated in Vietnam and the Philippines for tolerance of acid sulfate conditions.

Recently, an intergeneric hybrid between *O. sativa* and a related salt-tolerant species, *Porteresia coarctata,* was produced through embryo rescue (Jena 1994, Brar et al 1997). The research staff of the University of Nottingham have also produced somatic hybrids through protoplast fusion between *O. sativa* and *P. coarctata.* Such hybrids offer great promise for increasing the genetic diversity of rice cultivars for increased salinity tolerance.

## Increasing cytoplasmic diversity in hybrid rice varieties

The use of hybrid rice offers another opportunity to enhance yield potential. Most commercial hybrids of indica rice are based on the wild abortive (WA) source of cytoplasmic male sterility (CMS), which was derived in 1970 from a common wild rice (*Oryza sativa* f. *spontanea*) growing on Hainan Island in China (Shih-Cheng and Yuan 1980). More than 9.5% of the rice hybrids grown in China have WA cytosterile cytoplasm (Yuan 1993). Such cytoplasmic uniformity increases the genetic vulnerability of hybrid rice to diseases and insects. To overcome this problem, diversification of the CMS source is needed. We crossed 45 accessions of *O. perennis* and four accessions of *O. rufipogon* as female parents with the widely grown varieties IR54 and IR64. Both IR54 and IR64 can restore the fertility of CMS lines possessing WA cytoplasm.

Of the backcross derivatives, one line with the cytoplasm of *O. rufipogon* (accession 104823) and the nucleus of IR64 was found to be stable for complete pollen sterility. (This accession was formerly referred to as *O. perennis* by several authors. According to the revised taxonomy of the *Oryza* genus—Table 1—it does belong to the *O. rufipogon* species.) The newly developed CMS line has been designated IR66707A. Crosses of IR66707A with six restorers of WA cytoplasm also showed almost complete pollen sterility, indicating that this source of CMS is different from that of WA cytoplasm. Molecular analysis of IR66707A and *O. rufipogon* with mitochondrial DNA-specific probes showed that IR66707A has the same mitochondrial genome as the donor *O. rufipogon.* Thus, CMS may not be caused by any major rearrangement or modification of mtDNA (Dalmacio et al 1995). Another CMS line having the cytoplasm of *O. glumaepatula* and the nuclear genome of IR64 has been developed. The two new CMS lines are valuable additions to the gene pool for cytoplasmic diversification of hybrid rice varieties. A search for restorers of these CMS lines is under way.

### Increasing genetic diversity for apomixis

Apomixis is asexual reproduction through seed, in which the embryo (seed) develops without the union of the egg and sperm. Apomictic seed is genetically identical to the maternal parent. Apomixis is being explored as a New Frontier Project for exploiting hybrid vigor in rice. Apomixis will enable poor farmers in developing countries to surmount the barrier of hybrid seed costs and reap the benefits of high-yielding hybrid rice technology. Apomixis is widespread; more than 300 plant species are known to be apomictic. Some of the wild relatives of major cereals, such as maize, pearl millet, and wheat, have been found to be apomictic. We have screened more than 100 accessions of tetraploid wild species of *Oryza,* but none of them showed any evidence of apospory. We are continuing to screen additional germplasm from secondary and tertiary gene pools of *Oryza* to identify apomictic strains. Once such stocks become available, apomixis could be transferred into rice through wide hybridization procedures. Synteny analysis and comparative mapping of cereal genomes offer great promise to isolate the gene(s) for apomixis from wild relatives such as *Tripsacum* and *Pennisetum* and to incorporate such genes through genetic engineering for developing apomictic rice.

## Policy issues

Historically and until recently, plant genetic resources—and obviously the genetic diversity present in them — could be collected and used freely, though not necessarily free of charge, by anyone. As Brush (1996) pointed out, however, use did not mean an open, unregulated access, but one based on the principle of common heritage, which implies reciprocity between collectors of genetic resources and producers. Landraces may be collected from farmers' fields, but improved crop varieties and other nonproprietary technologies return to them (Brush 1996). This principle has certainly governed IRRI varieties and technology. All nations have benefited from the free access to and exchange of germplasm (Jackson 1995).

Two recent developments are changing the status of plant genetic resources as a common heritage good: (1) the Convention on Biological Diversity (CBD), and (2) changes in intellectual property rights (IPR) worldwide.

The CBD is a framework agreement for the conservation and sustainable use of biological diversity and is a legally binding international law for those states that have signed and ratified it. It recognizes the sovereignty of countries over biological resources and establishes a framework to regulate access to them, based on mutually agreed terms and subject to prior informed consent. Together with a global plan of action on the environment and development, Agenda 21, which is not legally binding, the CBD signals a global commitment to fostering sustainable development and the conservation and sustainable use of biological diversity and the fair and equitable sharing of benefits arising out of the use of genetic resources.

The regulation of access to plant genetic resources can have positive effects on their use and conservation, because it allows countries to benefit from them. But it should not become a barrier to international cooperation (Cooper et al 1994). This understanding is important given the fundamental role that access to and exchange of these resources have for the food supply of all countries. For example, the Rice Germplasm Center distributed more than 410,000 packets of rice seeds to researchers around the world between 1986 and 1995, and INGER has facilitated the global exchange of rice germplasm among Asia, Africa, and Latin America. Since INGER's inception, more than 600 rice varieties have been released through the network (M. Jackson, IRRI, personal communication). Developing nations have benefited tremendously from these flows.

An issue of much concern has been the status of the *ex situ* collections acquired before the CBD came into force in late December 1993. This has been an important issue for IRRI because of its important *ex situ* collection. Along with the other CGIAR centers with germplasm collections, IRRI has concluded an agreement with the Food and Agriculture Organization of the United Nations (FAO) to place its collection under the auspices of FAO in an International Network of *Ex Situ* Collections, under which the trusteeship concept will be recognized by the intergovernmental body (Jackson 1995). IRRI will supply the genetic resources held in trust under a Materials Transfer Agreement (MTA) designed to ensure the free availability of materials and genes derived directly from them (IRRI 1996b).

As we have pointed out, IPR issues become important in the use and conservation of plant genetic resources in general and of rice in particular. Although IPR for crop varieties have been present for a long time in many countries, new developments in biotechnology, new trade agreements such as the Uruguay Round, the creation of the World Trade Organization, and the strengthening of the private sector worldwide have brought IPR to the forefront. IPR currently tend to be stricter and more restrictive. The pros and cons of IPR for plant genetic resources continue to be debated in academic and policy forums, as well as in the courts. An IRRI policy, approved by the Institute's Board of Trustees in September 1994, states that no intellectual property protection on the designated germplasm will be sought. This policy includes four protocols: (1) rice genetic resources; (2) breeding lines, elite germplasm, and hybrid rice; (3) inventions and materials derived from biotechnology; and (4) agricultural equipment, publications, databases, and software. As it pertains to the rice genetic resources held in trust by IRRI, this policy clearly states that they "will be made available on the understanding that the recipients will take no steps which restrict their further availability to other interested parties" (IRRI 1996b).

Finally, we should mention a key agreement for the future of international cooperation on plant genetic resources—the FAO International Undertaking on Plant Genetic Resources. It is aimed at ensuring "...that plant genetic resources of economic or social interest, particularly for agriculture, will be explored, preserved, evaluated, and made available for plant breeding and scientific purposes" (FAO 1993). Important differences exist between this document and the CBD, and efforts are under way to harmonize the former with the latter.

The International Undertaking is the cornerstone of the FAO Global System on Plant Genetic Resources, which also includes the Commission on Genetic Resources for Food and Agriculture. Three elements of this system are: (1) an internationally coordinated network of national, regional, and international centers, including an international network of base collections in genebanks, under the auspices and jurisdiction of FAO; (2) a global information system on plant genetic resources; and (3) an early warning system to identify any hazards that threaten the efficient maintenance and operation of a plant genetic resources collection (FAO 1993).

A major event for the use and conservation of plant genetic resources was the International Technical Conference on Plant Genetic Resources held in Leipzig, Germany, 17-23 June 1996. At this conference, the Global Plan of Action and the Leipzig Declaration on Conservation and Sustainable Utilization of Plant Genetic Resources for Food and Agriculture were adopted. The Global Plan of Action is based on the Report on the State of the World's Plant Genetic Resources. This report was prepared with the participation of 154 countries, as well as other organizations, such as individual CGIAR centers. The Global Plan of Action will guide genetic resources activities and funding opportunities for at least the next decade.

The Global Plan of Action addresses priority activities in four areas:

- *In situ* conservation and development
- *Ex situ* conservation
- Use of plant genetic resources
- Institution and capacity building

IRRI is already either working or planning to work on several of these activities. Examples of current work that addresses these issues include (1) supporting on-farm conservation and plant improvement through research on the socioeconomic and genetic aspects of farmer-managed rice systems; (2) sustaining existing *ex situ* collections, for which the IRG facilities have been upgraded (the genebank meets all the approved or preferred FAO genebank standards for *ex situ* conservation); (3) regenerating threatened *ex situ* accessions, for which extensive research has been carried out on the optimum conditions at Los Baños for seed regeneration and multiplication; and (4) supporting the collection of plant genetic resources, for which IRRI (with the help of the Swiss Agency for Development and Cooperation and in collaboration with national programs in Asia, Africa, and Latin America) is accelerating the collection of rice landrace varieties in regions where little collecting has been done.

## Challenges

Continued and increased use of genetic diversity should be available in genebanks and in farmers' fields. Emphasis should be given to increasing genetic diversity in rice germplasm by conventional breeding, as well as through tissue culture and genetic engineering techniques. Useful genetic variability present in the primary and secondary gene pools of *Oryza* should be exploited to widen the gene pool of cultivated rice varieties. New and more genetically diverse varieties need to be deployed in farmers' fields. These varieties need to address evolving farmer and consumer needs, particularly in heterogeneous environments.

One of the major concerns in the maintenance and use of biodiversity is the widespread loss of genetic diversity of the germplasm. Intensification of agriculture has brought soil erosion, deforestation, environmental degradation, and loss of genetic diversity. So far, plant breeding practices have not been able to prevent this loss. Therefore, we urgently need to strengthen the collection, conservation, and deployment of genetic resources. Although *ex situ* conservation for rice is well developed, understood, and the most cost-effective method of conservation, it also has limitations. Space for seed storage is always limited. We cannot conserve all genetic resources *ex situ.* Furthermore, it is static compared with the materials at their original sites; evolution of the germplasm is completely stopped and it cannot guarantee the genetic integrity of the germplasm because samples are limited. Genetic erosion of the conserved germplasm does occur in some genebanks with inappropriate processing of materials during, for example, seed increase, rejuvenation, and other activities. Overcoming these limitations is a challenge to rice scientists.

*In situ* conservation can address some of these limitations, particularly for wild relatives, because it is dynamic and favors continued evolution. It also needs to be further promoted. The use of molecular markers to precisely characterize genetic diversity in the germplasm needs to be encouraged. But *in situ* conservation also has limitations. We lack knowledge on the population dynamics (population structure, gene flow, etc.) of wild species and on their habitats and dynamics. We may experience conflicts between economic development and the conservation of wild species *in situ.* We need to evaluate the potential contribution of on-farm conservation to the conservation of the rice gene pool, in terms of both its socioeconomic and genetic feasibility.

The challenges that the implementation of the CBD and the changing aspects of IPR give to farmers, consumers, and policymakers, both at the country and international levels, are to balance public and private interests for the benefit of current and future generations. This is an even more difficult task because of the global scope of germplasm resources. History has shown that cooperation in the flows and use of germplasm has produced enormous benefits for humanity. Because of the threats to genetic diversity, this cooperation is also fundamental to conservation. IRRI is committed to maintaining this cooperation and to ensuring that the plant genetic resources of rice continue to benefit all rice-producing and rice-consuming nations, particularly the poor farmers in those countries where the germplasm originated.

## References

Aggarwal RK, Brar DS, Khush GS. 1997. Two new genomes in the *Oryza* complex identified on the basis of molecular divergence analysis using total genomic DNA hybridization. Mol. Gen. Genet. 254:1-12.

Altieri MA, Merrick LC. 1987. In situ conservation of crop genetic resources through maintenance of traditional farming systems. Econ. Bot. 41:86-96.

Amante-Bordeos A, Sitch LA, Nelson R, Dalmacio RD, Oliva NP, Aswidinnoor H, Leung H. 1992. Transfer of bacterial blight and blast resistance from the tetraploid wild rice *Oryza minuta* to cultivated rice, *Oryza sativa.* Theor. Appl. Genet. 84:345-354.

Appa Rao S, Bounphanouxay C, Phetpaseut V, Schiller JM, Phannourath V, Jackson MT. 1997. Collection and preservation of rice germplasm from southern and central regions of the Lao PDR. Lao J. Agric. For. 1:43-56.

Barr ME. 1977. Magnaporthe, Telimenella, and Hyponectria (Physosporellaceae). Mycologia 69:952-956.

Bellon MR. 1996. The dynamics of crop infraspecific diversity: a conceptual framework at the farmer level. Econ. Bot. 50:26-39.

Bellon MR, Pham JL, Jackson MT. 1997. Genetic conservation: a role for rice farmers. In: Maxted N, Ford-Lloyd BV, Hawkes JG, editors. Plant conservation: the in situ approach. London (UK): Chapman and Hall. p 263-289.

Bellon MR. 1991. The ethnoecology of maize variety management: a case study from Mexico. Hum. Ecol. 19:389-418.

Brar DS, Khush GS. 1986. Wide hybridization and chromosome manipulation in cereals. In: Evans DA, Sharp WR, Ammirato PV, editors. Handbook of plant cell culture. Vol. 4. Techniques and applications. New York, N.Y. (USA): Macmillan Publishing Co. p 221-263.

Brar DS, Khush GS. 1995. Wide hybridization for enhancing resistance to biotic and abiotic stresses in rainfed lowland rice. In: Fragile lives in fragile ecosystems. Manila (Philippines): International Rice Research Institute. p 901-910.

Brar DS, Dalmacio R, Elloran R, Aggarwal R, Angeles R, Khush GS. 1996. Gene transfer and molecular characterization of introgression from wild *Oryza* species into rice. In: Rice genetics III. Manila (Philippines): International Rice Research Institute. p 477-486.

Brar DS, Elloran RM, Talag JD, Abbasi F, Khush GS. 1997. Cytogenetic and molecular characterization of an intergeneric hybrid between *Oryza sativa* L. and *Porteresia coarctata* (Roxb.) Tateoka. Rice Genet. Newsl. 14:43-45.

Brown AHD, Schoen DJ. 1992. Plant population genetic structure and biological conservation. In: Sandlund OT, Hindar K, Brown AHD, editors. Conservation of biodiversity for sustainable development. Oslo (Norway): Scandinavian University Press. p 88-104.

Brush SB. 1995. In situ conservation of landraces in centers of crop diversity. Crop Sci. 35:346-354.

Brush SB. 1996. Is common heritage outmoded? In: Brush SB, Stabinsky D, editors. Valuing local knowledge. Washington, D.C. (USA): Island Press. p 143-164.

Brush SB, Taylor JE, Bellon MR. 1992. Biological diversity and technology adoption in Andean potato agriculture. J. Dev. Econ. 39:365-387.

Brush SB. 1991. A farmer-based approach to conserving crop germplasm. Eon. Bot. 45:153-165.

Byerlee D. 1994. Modern varieties, productivity, and sustainability: recent experience and emerging challenges. Mexico: International Maize and Wheat Improvement Center.

Causse MA, Fulton TM, Cho YG, Ahn SN, Chunwongse J, Wu KS, Xiao JH, Yu ZH, Ronald PC, Harrington SE, Second G, McCouch SR, Tanksley SD. 1994. Saturated molecular map of the rice genome based on an interspecific backcross population. Genetics 138:1251-1274.

Chang TT. 1976. The origin, evolution, cultivation, dissemination, and diversification of Asian and African rices. Euphytica 25:435-441.

Chang TT. 1984. Conservation of rice genetic resources: luxury or necessity? Science 224:251-256.

Chang TT. 1994. The biodiversity crisis in Asia: crop production and remedial measures. In: Peng CI, Chou CH, editors. Biodiversity and terrestrial ecosystems. Institute of Botany, Academia Sinica Monograph Series No. 14. Taipei (Taiwan): Academia Sinica.

Chatterjee D. 1951. Note on the origin and distribution of wild and cultivated rices. Indian J. Agric. Sci. 18:185-192.

Clegg MT, Giddings LV, Lewis CS, Barton JH, editors. 1993. Report of the international consultation on rice biosafety in Southeast Asia, 1-2 Sept. 1992. Technical paper, Biotechnology Series No. 1. New York, N.Y. (USA): World Bank.

Conklin HC. 1957. Hanundo agriculture: a report on an integral system of shifting cultivation in the Philippines. FAO Forestry Development Paper No. 12. Rome (Italy): FAO.

Cooper D, Engels J, Frison E. 1994. A multilateral system for plant genetic resources: imperatives, achievements and challenges. Issues in Genetic Resources No. 2. Rome (Italy): International Plant Genetic Resources Institute.

Cooper D, Vellvé R, Hobbelink H. 1992. Growing diversity: genetic resources and local food security. London (UK): Intermediate Technology Publications.

Cuevas-Pérez FE, Guimaraes EP, Berrío LE, González DI. 1992. Genetic base of irrigated rice in Latin America and the Caribbean. Crop Sci. 32:1054-1059.

Dalmacio R, Brar DS, Ishii T, Sitch LA, Virmani SS. Khush GS. 1995. Identification and transfer of a new cytoplasmic male sterility source from *Oryza perennis* into indica rice (*O. sativa* ). Euphytica 82:221-225.

Dalrymple DG. 1986. Development and spread of high-yielding rice varieties in developing countries. Washington, D.C. (USA): Agency for International Development.

de Janvry A, Fafchamps M, Sadoulet E. 1991. Peasant household behavior with missing markets—some paradoxes explained. Econ. J. 101:1400-1417.

de Leon JC. 1994. Genetic relationships among Philippine-bred rice varieties as determined by pedigree- and morphology-based measures. Unpublished MS thesis. University of the Philippines, Los Baños, Laguna, Philippines.

de Leon JC, Carpena AL. 1995. Pedigree-based genetic diversity analysis of improved rice (*Oryza sativa* L.) varieties in the Philippines. Philipp. J. Crop Sci. 20:1-12.

Dennis JV. 1987. Farmer management of rice variety diversity in northern Thailand. Unpublished PhD dissertation. Cornell University, Ithaca, New York, USA.

Dilday RH. 1990. Contribution of ancestral lines in the development of new cultivars of rice. Crop Sci. 30:905-911.

Evenson RE, Collin D. 1997. Genetic resources, international organizations, and improvement in rice varieties. Econ. Dev. Cult. Change 45:471-500.

Eyzaguime P, Iwanaga M, editors. 1995. Participatory plant breeding. Proceedings of a workshop on participatory plant breeding, 26-29 July 1995, Wageningen, The Netherlands. Rome (Italy): International Plant Genetic Resources Institute.

FAO (Food and Agriculture Organization). 1993. The international undertaking on plant genetic resources. Commission on Plant Genetic Resources CPGR/93/Inf. 2, Rome.

Ford-Lloyd BV, Jackson MT. 1986. Plant genetic resources: an introduction to their conservation and use. London (UK): Edward Arnold.

Frankel OH, Brown AHD, Burdon JJ. 1995. The conservation of plant biodiversity. Cambridge (UK): Cambridge University Press.

Fujimoto H, Itoh K, Yamamoto M, Kyozuka J, Shimamoto K. 1993. Insect-resistant rice generated by introduction of a modified delta endotoxin gene of *Bacillus thuringiensis.* Biotechnology 11:1151-1155.

Ghareyazie B, Huang N, Second G, Bennett J, Khush GS. 1995. Classification of rice germplasm. I. Analysis using ALP and PCR-based RFLP. Theor. Appl. Genet. 91:218-227.

Glaszmann JC. 1987. Isozymes and Asian rice varieties. Theor. Appl. Genet. 74:21-30.

Glaszmann JC. 1988. Geographic pattern of variation among Asian native cultivars (*Oryza sativa* L.) based on fifteen isozyme loci. Genome 30:782-792.

Hamrick JL, Godt MJ. 1989. Allozyme diversity in plant species. In: Brown AHD, Clegg MT, Kahler AL, Weir WS, editors. Plant population genetics, breeding and genetic resources. Sunderland, Mass. (USA): Sinauer Associates Inc. Publishers. p 43-63.

Hargrove TR. 1979. Diffusion and adoption of semidwarf rice cultivars as parents in Asian rice breeding programs. Crop Sci. 19:571-574.

Hargrove TR, Coffman WR, Cabanilla VL. 1980. Ancestry of improved cultivars of Asian rice. Crop Sci. 20:721-727.

Harlan JR, de Wet JMJ. 1971. Toward a rational classification of cultivated plants. Taxon 20:509-517.

Hayakawa T, Zhu Y, Itoh K, Kimura Y, Izawa T, Shimamoto K, Toriyama S. 1992. Genetically engineered rice resistant to rice stripe virus, an insect-transmitted virus. Proc. Natl. Acad. Sci. USA 89:9865-9869.

Heszky LE, Simon-Kiss I. 1992. DAMA: the first plant variety of biotechnology origin in Hungary, registered in 1992. Hungarian Agric. Res. 1:30-32.

Heywood VH, editor. 1995. Global biodiversity assessment. Cambridge (UK): Cambridge University Press.

Hossain M. 1995. Sustaining food security for fragile environments in Asia: achievements, challenges, and implications for rice research. In: Fragile lives in fragile ecosystems. Manila (Philippines): International Rice Research Institute. p 3-23.

IPGRI (International Plant Genetic Resources Institute). 1993. Diversity for development: the strategy of the International Plant Genetic Resources Institute. Rome (Italy): IPGRI.

IRRI (International Rice Research Institute). 1982. IR36: the world's most popular rice. Manila (Philippines): IRRI.

IRRI (International Rice Research Institute). 1992. Challenges and opportunities in a less favorable ecosystem: rainfed lowland rice. IRRI Information Series No. 1. Manila (Philippines): IRRI.

IRRI (International Rice Research Institute). 1993. Challenges and opportunities in a less favorable ecosystem: upland rice. IRRI Information Series No. 2. Manila (Philippines): IRRI.

IRRI (International Rice Research Institute). 1994. Challenges and opportunities in a less favorable ecosystem: flood-prone rice. IRRI Information Series No. 4. Manila (Philippines): IRRI.

IRRI (International Rice Research Institute). 1995. World rice statistics 1993-94. Manila (Philippines): IRRI.

IRRI (International Rice Research Institute). 1996a. *Bt* rice: research and policy issues. IRRI Information Series No. 5. Manila (Philippines): IRRI.

IRRI (International Rice Research Institute). 1996b. Policy on intellectual property rights. Manila (Philippines): IRRI.
Ishii T, Brar DS, Multani DS, Khush GS. 1994. Molecular tagging of genes for brown planthopper resistance and earliness introgressed from *Oryza australiensis* into cultivated rice. Genome 37:217-221.
Jackson MT. 1995. Protecting the heritage of rice biodiversity. GeoJournal 35:267-274.
Jackson MT, Huggan R. 1993. Sharing the diversity of rice to feed the world. Diversity 9:22-25.
Jena KK, Khush GS. 1990. Introgression of genes from *Oryza officinalis* Well ex Watt to cultivated rice, *O. sativa* L. Theor. Appl. Genet. 80:737-745.
Jena KK. 1994. Production of intergeneric hybrid between *Oryza sativa* and *Porteresia coarctata* T. Curr. Sci. 67:744-746.
Kareiva P, Morris W, Jacobi CM. 1994. Studying and managing the risk of cross-fertilization between transgenic crops and wild relatives. Mol. Ecol. 3:15-21,
Khush GS. 1977. Disease and insect resistance in rice. Adv. Agron. 29:265-361.
Khush GS. 1984. Terminology for rice-growing environments. Manila (Philippines): International Rice Research Institute.
Khush GS. 1989. Multiple disease and insect resistance for increased yield stability in rice. In: Progress in irrigated rice research. Manila (Philippines): International Rice Research Institute. p 79-92.
Khush GS, Bacalangco E, Ogawa T. 1990. A new gene for resistance to bacterial blight from *O. longistaminata.* Rice Genet. Newsl. 7:121-122.
Khush GS, Brar DS. 1992. Overcoming the barriers in hybridization. Theor. Appl. Genet. Vol. 16 (monograph):47-61.
Khush GS, Brar DS, Zapata FJ, Nelson R, McCouch S, Bottrell DG. 1994. Rice biotechnology at IRRI. In: Toward enhanced and sustainable agricultural productivity in the 2000s: breeding research and biotechnology. Proceedings of the 7th International Congress, SABRAO, and International Symposium. World Sustainable Agricultural Association (WSAA). Taiwan District Agricultural Association and Society for the Advancement of Breeding Research in Asia and Oceania. p 387-414.
Khush GS, Ling KC, Aquino RC, Aguiero VM. 1977. Breeding for resistance to grassy stunt in rice. 3rd International Congress, Society for the Advancement of Breeding Research in Asia and Oceania (SABRAO), 12-13 Feb 1977, Canberra, Australia.
Kshirsagar KG, Pandey S. 1996. Diversity of rice cultivars in a rainfed village in the Orissa state of India. In: Sperling L, Loevinsohn M, editors. Using diversity: enhancing and maintaining genetic resources on-farm. Proceedings of a workshop held 19-21 June 1995, New Delhi, India. New Delhi (India): International Development Research Centre. p 55-65.
Lambert DH. 1985. Swamp rice farming: the indigenous pahang Malay agricultural system. Boulder, Colo. (USA): Westview Press.
Lando RP, Mak S. 1994a. Rainfed lowland rice in Cambodia: a baseline study. IRRI Research Paper Series 152. Manila (Philippines): International Rice Research Institute.
Lando RP, Mak S. 1994b. Deepwater rice in Cambodia: a baseline survey. IRRI Research Paper Series 153. Manila (Philippines): International Rice Research Institute.
Lando RP, Mak S. 1994c. Cambodian farmers' decision making in the choice of traditional rainfed lowland rice varieties. IRRI Research Paper Series 154. Manila (Philippines): International Rice Research Institute.

Lin MS. 1991. Genetic base of Japonica rice varieties released in Taiwan. Euphytica 56:43-46.

Lin W, Anuratha CS, Datta K, Potrykus I, Muthukrishnan S, Datta SK. 1995. Genetic engineering of rice for resistance to sheath blight. Biotechnology 13:686-691.

Ling KC, Aquiero VM, Soon Hyung Lee. 1970. A mass screening method for testing resistance to grassy stunt disease of rice. Plant Dis. Rep. 54:565-569.

Lipton M, Longhurst R. 1989. New seeds and poor people. London (UK): Unwin Hyman.

Louette DA, Charrier A, Berthand J. 1997. In situ conservation of maize in Mexico: genetic diversity and maize seed management in a traditional community. Econ. Bot. 51:20-38.

Matsuo T. 1952. Genecological studies on cultivated rice. Bull. Natl. Inst. Agric. Sci. Jpn. D3:1-111.

Maurya DM, Bottrall A, Fanington J. 1988. Improved livelihoods, genetic diversity and farmer participation: a strategy for rice breeding in rainfed areas of India. Exp. Agric. 24:311-320.

Morishima H, Sano Y, Oka HI. 1980. Observations on wild and cultivated rices and companion weeds in the hilly areas of Nepal, India and Thailand: report of a study tour in tropical Asia, 1979. Report, National Institute of Genetics, Misima, Japan.

Multani DS, Jena KK, Brar DS, de los Reyes BG, Angeles E, Khush GS. 1994. Development of monosomic alien addition lines and introgression of genes from *Oryza australiensis* Domin. to cultivated rice, *O. sativa* L. Theor. Appl. Genet. 88:102-109.

Mundt CC. 1994. Techniques to manage pathogen coevolution with host plants to prolong resistance. In: Teng PS, Heong KL, Moody K, editors. Rice pest science and management. Manila (Philippines): International Rice Research Institute. p 193-205.

NRC (National Research Council). 1993. Managing global genetic resources: agricultural crop issues and policies. Washington, D.C. (USA): National Academy Press.

Ogura H, Shimamoto K. 1991. Field performance of protoplast derived rice plants and the release of a new variety. In: Bajaj YPS, editor. Biotechnology in agriculture and forestry. Vol. 14. Rice. Berlin (Germany): Springer-Verlag.

Oka HI. 1953. Phylogenetic differentiation of the cultivated rice plant. IX. Influence of intervarietal hybrid sterility on segregation ratios in rice. Jpn. J. Breed. 3:31-39.

Oka HI. 1974. Experimental studies on the origin of cultivated rice. Genetics 78:475-486.

Oka HI. 1988. Origin of cultivated rice. Developments in crop science, 14. Tokyo (Japan): Japan Scientific Societies Press.

Oldfield ML, Alcorn JB. 1987. Conservation of traditional agroecosystems. Bioscience 37:199-208.

Otsuka K, Gascon F, Asano S. 1994. Second-generation MVs and the evolution of the Green Revolution: the case of Central Luzon, 1966-90. Agric. Econ. 10:283-295.

Pandey S. 1996. Socioeconomic context and priorities for strategic research on Asian upland rice ecosystems. In: Piggin C et al, editors. Upland rice research in partnership. Proceedings of the Upland Rice Consortium Workshop, 4-13 Jan. 1996, Padang, Indonesia. IRRI Discussion Paper Series No. 16. Manila (Philippines): International Rice Research Institute. p 103-124.

Peng S, Khush GS, Cassman KG. 1994. Evolution of the new plant ideotype for increased yield potential. In: Cassman K, editor. Breaking the yield barrier. Manila (Philippines): International Rice Research Institute.

Pham JL. 1991. Genetic diversity and intervarietal relationships in rice (*Oryza sativa* L.) in Africa. In: Rice genetics II. Manila (Philippines): International Rice Research Institute. p 55-65.

Pham JL, Glaszmann JC, Sano R, Barbier P, Ghesquière A, Second G. 1990. Isozyme markers in rice: genetic analysis and linkage relationships. Genome 33:348-359.
Pham JL, Ghesquière A, Second G. 1994. On-farm conservation of rice genetic resources based on the management of populations made with landraces. In: Discussion Workshop on On-Farm Conservation of Crop Genetic Resources. Manila (Philippines): International Rice Research Institute.
Pham JL, Bellon MR, Jackson MT. 1996. A research program for on-farm conservation of rice genetic resources. Int. Rice Res. Notes 21:10-11.
Plattner S. 1989. Economic behavior in markets. In: Plattner S, editor. Economic anthropology. Stanford, Calif. (USA): Stanford University Press. p 209-221.
Plucknett DL, Smith NHJ, Williams JT, Anishetty NM. 1987. Gene banks and the world's food. Princeton, N.J. (USA): Princeton University Press.
Portères R. 1950. Vieilles agricultures de 1'Afrique intertropicales: centres d'origine et de diversification variétale primaire et berceaux d'agriculture anterieurs au XVIème siècle. Agron. Trop. 5:489-507.
Richards P. 1986. Coping with hunger: hazard and experiment in an African rice-farming system. London (UK): Allen and Unwin.
Ronald PC, Tanksley SD. 199 1. Genetic and physical analysis of the bacterial blight resistance gene, *Xa-21*. Rice Genet. Newsl. 8:142-143.
Sampath S, Govindaswami S. 1958. Wild rices of *Oryza* and their relationship to the cultivated varieties. Rice News Teller 6(3):17-20.
Sampath S, Rao MBVN. 1951. Interrelationships between species in genus *Oryza*. Indian J. Genet. Plant Breed. 11:14-17.
Sarkarung S. 1995. Breeding rice cultivars suitable for rainfed lowland environments: a farmers participatory approach for eastern India. In: Eyzaguirre P, lwanaga M, editors. Participatory plant breeding. Proceedings of a workshop on participatory plant breeding, 26-29 July 1995, Wageningen, The Netherlands. Rome (Italy): International Plant Genetic Resources Institute. p 123-127.
Second G. 1982. Origin of the genetic diversity of cultivated rice (*Oryza* spp.): study of the polymorphism scored at 40 isozyme loci. Jpn. J. Genet. 57:25-57.
Second G. 1991. Molecular markers in rice systematics and the evaluation of genetic resources. In: Bajaj YPS, editor. Rice. Biotechnology in agriculture and forestry, 14. New York, N.Y. (USA): Springer-Verlag. p 468-494.
Second G, Ghesquière A. 1995. Cartographie des introgressions rèciproques entre les deux sous-espèces indica et japonica de riz cultivé (*Oryza sativa* L.). In: Colloque "Techniques et utilisation des marqueurs moléculaires", Montpellier, France, 29-31 mars 1994. Les Colloques, n°72. Paris (France): Editions INRA. p 83-93.
Second G, Parco A, Caiole A. 1995. The hybrid origin hypothesis of cultivated rice *(Oryza sativa)* explains some of the gaps in its RFLP map and suggests an efficient mapping population for useful genes and QTLs. In: Tsunewaki K, editor. Plant genome and plastome: their structure and evolution. Tokyo (Japan): Kodansha Scientific. p 129-136.
Shih-Cheng L, Yuan LP. 1980. Hybrid rice breeding in China. In: Innovative approaches to rice breeding. Manila (Philippines): International Rice Research Institute. p 35-51.
Sitch LA. 1990. Incompatibility barriers operating in crosses of *Oryza sativa* with related species and genera. In: Gustafson JP, editor. Gene manipulation in plant improvement. New York, N.Y. (USA): Plenum Press. p 77-93.
Sperling L, Loevinsohn ME. 1995. New division of labor between farmers and breeders unites conservation and development. Diversity 11:5-7.

Sperling L, Loevinsohn ME, Ntabomvura B. 1993. Rethinking the farmer's role in plant breeding: local bean experts and on-station selection in Rwanda. Exp. Agric. 29:509-519.

Sutlive VH. 1978. The Iban of Sarawak. Arlington Heights, Va. (USA): AHM Publishing Co.

Vaughan DA. 1989. The genus *Oryza* L.: current status of taxonomy. IRRI Research Paper Series 138. Manila (Philippines): International Rice Research Institute.

Vaughan DA, Chang TT. 1992. In situ conservation of rice genetic resources. Econ. Bot. 46:368-383.

Virk PS, Ford-Lloyd BV, Jackson MT, Pooni HS, Clemeno TP, Newbury HJ. 1996. Predicting quantitative variation within rice germplasm using molecular markers. Heredity 76:296-304.

Virk PS, Newbury HJ, Jackson MT, Ford-Lloyd BV. 1995. The identification of duplicate accessions within a rice germplasm collection using RAPD analysis. Theor. Appl. Genet. 90:1049-1055.

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

Wang ZY, Tanksley SD. 1989. Restriction fragment length polymorphism in *Oryza sativa* L. Genome 32:1113-1118.

Wilkes HG. 1989. Germplasm preservation: objectives and need. In: Knutson L, Stoner AK, editors. Diversity and germplasm preservation: global imperatives. Kluwer Academic Press, The Netherlands.

Witcombe J, Joshi A. 1995. Farmer participatory approaches for varietal breeding and selection and linkages to the formal seed sector. In: Eyzaguirre P, Iwanaga M, editors. Participatory plant breeding. Proceedings of a workshop on participatory plant breeding, 26-29 July 1995, Wageningen, The Netherlands. Rome (Italy): International Plant Genetic Resources Institute. p 57-65.

Wu KS, Tanksley SD. 1993. Abundance, polymorphism and genetic mapping of microsatellites in rice. Mol. Gen. Genet 241:225-235.

Xiao JH, Grandillo S, Ahn SN, McCouch SR, Tanksley SD, Li JM, Yuan L. 1996. Genes from wild rice improve yield. Nature 384:223-224.

Yu LX, Nguyen HT. 1994. Genetic variation detected with RAPD markers among upland and lowland rice cultivars (*Oryza sativa* L.). Theor. Appl. Genet. 87:668-672.

Yuan LP. 1993. Advantages of and constraints to the use of hybrid rice varieties. In: Wilson KJ, editor. International Workshop on Apomixis in Rice. Changsha (China): Hunan Hybrid Rice Research Center.

## Notes

*Authors' addresses:* M.R. Bellon, International Maize and Wheat Improvement Center, Lisboa 27, Apartado Postal 6-641, 06600 Mexico, D.F., Mexico; D.S. Brar, B.R. Lu, and J.L. Pham, International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines.
m.bellon@clphac.cimmyt.mx d.brar@cgnet.com l.baorong@cgnet.com
j.pham@cgnet.com

*Acknowledgments:* We thank Drs. B. Courtois and K. Fischer for their helpful comments and Dr. M.T. Jackson for providing us with useful material on policy issues.

*Citation:* Dowling NG, Greenfield SM, Fischer KS, editors. 1998. Sustainability of rice in the global food system. Davis, Calif. (USA): Pacific Basin Study Center, and Manila (Philippines): International Rice Research Institute.

CHAPTER 17

# Biological diversity of rice landscapes

K. Schoenly, T.W. Mew, and W. Reichardt

A tropical rice field offers a biologically diverse and dynamic environment for microbial, floral, invertebrate, and vertebrate populations to flourish shortly after fields are flooded and well after canopy closure. A significant challenge is how to inventory, characterize, and assess such biodiversity in an agroecosystem of staggering taxonomic richness, interconnectedness, and spatiotemporal flux. For invertebrate biodiversity, research indicates that most insect pests are controlled by the activity of not just a few natural enemies, but a whole array, through a complex and rich food web of generalist and specialist predators and parasites that live above, below, and at the water surface as well as in flooded and aerated soil habitats. Microbial communities in the soil and on the rice plant, functioning as biocatalytic and antagonistic agents, may also have sufficient similarity in functions to maintain ecosystem-level processes within narrow limits. The roles that such functionally diverse organisms play as stabilizing and buffering agents in rice production systems remain to be discovered through future laboratory and field research.

Current integrated pest management (IPM) strategies in tropical rice production emphasize the use of host-plant resistance, cultural practices, and biological control for maintaining low pest populations with insecticides used as a method of last resort. A significant challenge in using IPM approaches is how to inventory, characterize, and assess the biocontrol effectiveness of natural enemies and microbial agents in an agroecosystem of staggering biodiversity, interconnectedness, and spatiotemporal flux whose inhabitants live in the plant canopy, on the water surface, in the floodwater, and in the soil (Fig. 1). The keystones to any rice biodiversity program are expert systematics, targeted over a wide taxonomic domain, an understanding of the natural history of a rice field, and quantitative tools directed at the population, community, and ecosystem levels. Moreover, because ecological communities possess too many species for each to be modeled by single-difference or differential equations and too few species with noticeably identical behavior to be statistically averaged, they qualify as “middle number systems” (O’Neill et al 1986, Allen and Starr 1982).

Current approaches for analyzing patterns and processes in tropical rice field communities have been borrowed from disciplines outside traditional agriculture, such as conservation biology (Meffe and Carroll 1994); biogeography (Myers and Giller

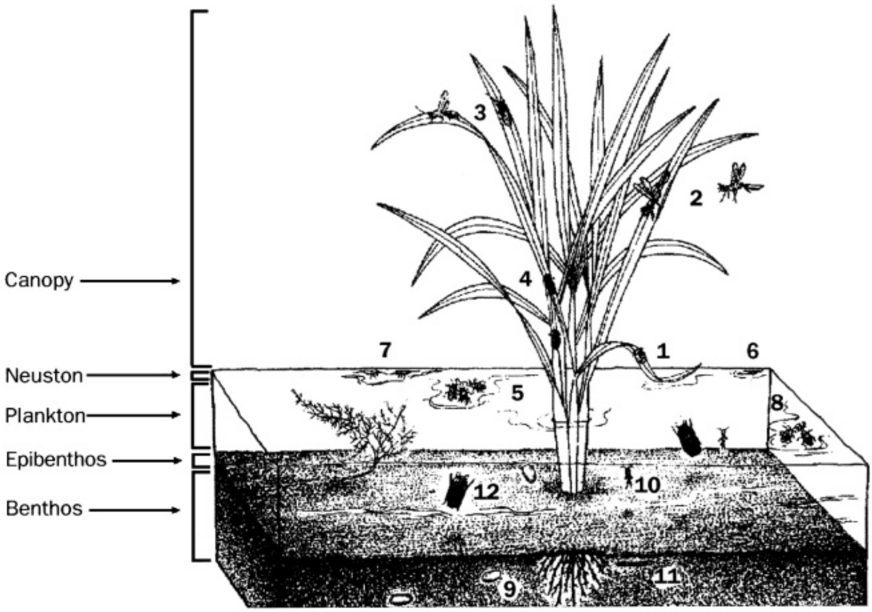



**Fig. 1.** Habitat zones and dominant taxa of an irrigated rice farmer's rice field in Calauan, Laguna, Philippines. Canopy taxa are *Stilbus* sp. adults (1), Chironomidae adults (2), *Cardiochiles philippinensis* adults (3), and *Egadrorna* sp. adults (4). Neustonic (water surface) taxa are *Microvelia atrolineata* adults (5), *Ephydra* sp. immatures (6), Entomobryidae adults (7), and *M. atrolineata* immatures (8). Planktonic and benthic taxa are *Heterocypris luzonensis* (9), *Eucyclops serrulatus* adults (10), Chironomidae immatures (11), and Hydrophilidae adults (12).

1988); community, statistical, and landscape ecology (Strong et al 1984, Ludwig and Reynolds 1988, Turner and Gardner 1991); systems science (e.g., Weinberg 1975); and numerical methods (Manly 1991).

A tropical rice field offers a biologically diverse and dynamic environment for microbial (prokaryotes and eukaryotes), floral (algae and weeds), invertebrate (insects, spiders, mites, mollusks, crustaceans), and vertebrate populations to flourish shortly after fields are flooded and well after canopy closure (Roger et al 1991, Schoenly et al 1996b, Settle et al 1996). Accumulated inventories of rice flora and fauna (Polhemus and Reisen 1976, Heckman 1979, Yano et al 1981,1982, Roger et al 1991, Catling 1992, Simpson et al 1993, Barrion and Litsinger 1995) have increased ecologists' understanding of rice communities and have recently permitted a quantitative assessment of certain farmer practices (Cohen et al 1994, Schoenly et al 1996a, Settle et al 1996). The basic tasks of sorting, counting, and identifying rice-associated taxa, however, require additional attention because ecological relationships within and between aquatic and terrestrial biota and between rice biota and farmer management practices remain poorly understood throughout Asia.

## Components of invertebrate diversity and current state of knowledge

An attempt to obtain a representative sample of the entire macroinvertebrate community of an irrigated rice farmer's field was made in Calauan, Laguna Province, Philippines, during the 1991 dry season (Schoenly et al 1998). In plots that received no pesticides, at least four community patterns were observed.

1. A majority of the macroinvertebrate taxa are found in the canopy layer (168/238 = 71%); however, greater abundance was noted below the canopy, with water surface (neustonic), floodwater (planktonic), soil-surface (epibenthic), and soil-burrowing (benthic) invertebrates constituting more than 90% of total invertebrate abundance. If function follows structure, then investigators who study canopy-only species may fail to observe community-level processes originating from the aquatic environment (e.g.. larval blooms of aquatic midges responding to elevated levels of organic matter).
2. Species abundance ranges from 1 individual per species to nearly 100,000 per species. This range of variation parallels some of the most species-rich habitats on the planet, such as vascular plants of southeastern United States temperate forests (Whittaker 1975), trees of tropical rain forests (Hubbell and Foster 1986), and pelagic invertebrates of the open seas (McGowan and Walker 1993).
3. The canopy, neustonic, and planktonic fauna each show low evenness in species abundance, with only 22 of 238 invertebrate taxa required to capture 95% of the total abundance. Most of these species are aquatic (19/22 = 86%), compared with only 3 (3/22 = 14%) from the plant canopy. The 12 taxa illustrated in Figure 1 come from this 22-taxa list.
4. In three of the five rice habitats (canopy, neustonic, and planktonic), common and rare species are uniformly distributed among each of four feeding guilds: detritivores (scavengers on dead organic matter), herbivores (rice, nonrice, and phytoplankton feeders), natural enemies (predators, parasitoids, and parasites), and "tourists" (accidental or incidental taxa). In the canopy and planktonic habitats, guild size follows the same descending sequence: natural enemies, herbivores, detritivores, and tourists. In an exceptional case, neustonic detritivores outnumber neustonic herbivores.

Taken together, these four patterns bolster previous claims that most rice pests are controlled by the activity of not just a few natural enemies, but a whole array, through a complex and rich web of generalist and specialist predators and parasites that live above, below, and at the water surface (Heckman 1979, Heong et al 1991, 1992, Schoenly et al 1996b, Settle et al 1996).

## Operational (function-based) concepts of rice diversity

The community approach detailed above provides methods and results for use as a reporting and training tool for analyzing biodiversity concepts of tropical rice ecosystems. This approach provides many practical opportunities to link biodiversity issues with rice IPM, Asian and Australian biogeography, and farmer practices (Schoenly et al 1996b). For example, classical biogeographical theory predicts that the invertebrate list for rice fields of Palawan (Philippines) and Vietnam, for example, would be more similar to one another than either would be to the rice-invertebrate list in New South Wales, Australia, because the fauna of New South Wales would contain more Australian than Oriental elements than either Palawan or Vietnam. If statistical analyses of these communities show that Palawan and Vietnam are indeed more similar to one another than to other regions, then a biocontrol measure effective in one of these two regions might be expected to be effective in the other because of similarities in species richness, composition, and functional groups (Schoenly et al 1996b). If future surveys are conducted using standard sampling methods and taxonomic keys, a biogeographical approach has applications to rice-invertebrate faunas besides those in Asia, to other ecological communities besides invertebrates, and to farmer practices such as pesticide spraying, varietal mixing, field burning, and intercropping.

The guild, as a functional unit, is a useful "middle-level'' descriptor for linking population- and ecosystem-level processes and is more constant, stable, and enduring than any of the taxa that compose it (O'Neill et al 1986). In tropical rice ecosystems, the guild concept is also useful as both a research tool for studying food web complexity and community dynamics (Heong et al 1991, 1992, Settle et al 1996) and a training tool in FAO farmers' field schools (Ooi 1996) for defining functional differences between pests, natural enemies, and detritivores (Settle et al 1996). Other analyses of rice-invertebrate communities show that the more abundant a species is, the more widely dispersed it is in a rice field (high coverage), and the longer is its residence time (high frequency of observation) over the growing season (Schoenly, unpublished data). This finding suggests that different measures of species importance (abundance, cover, frequency) may be interchangeable. The most useful index of species importance for rice communities, however, is likely to be based on species productivity (g of biomass produced $m^{-3}$ $d^{-1}$) because this quantifies the species' use of resources for population growth (Whittaker 1975).

If a close correspondence exists between a species' importance, as defined by ecologists, and its conspicuousness (ability to be seen by virtue of its abundance, size, etc.), then some or all of the 12 common taxa in Fig. 1 should be seen by other observers, including farmers, at other sites and times in the same field. A practical question for further study is how rice farmers would rank these taxa on a scale of perceived importance.

## Rice fields as ecological landscapes

### Practical issues of rice landscape conservation

Agricultural practices "geometricize the land" (Forman 1995) by replacing nature's soft curves and landscape heterogeneity with hard, straight, and uniform lines of mechanization. Because landscape losses beget invertebrate losses in diversity (Bell et al 1991), plowing, mowing, and other farming practices may disrupt biocontrol link-

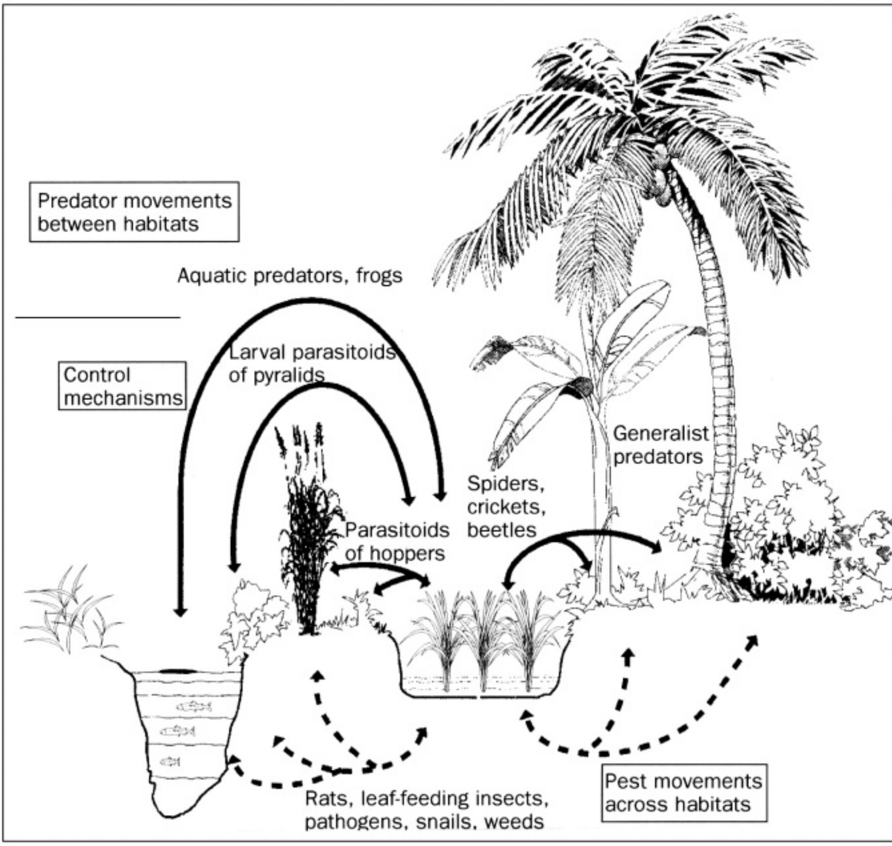



**Fig. 2.** Landscape features and organism associations of the rice ecosystem.

ages between rice pests and their natural enemies. In tropical rice, for example, levees (bunds) are refuges for some early season predators (e.g., spiders and ants) that are incapable of long-distance dispersal (Heong 1996), whereas certain bordering grasses (e.g., *Paspalum* spp.) support sizable populations of crickets (e.g., *Anaxipha longipennis, Metioche vittaticollis*) that are efficient predators of rice leaffolder eggs (de Kraker 1995) (Fig. 2). Identifying, testing, and deploying promising spatial features of crop landscapes for enhanced biological control is a natural next step in rice biodiversity research.

## Enhancing biological control through field landscape manipulation

The guiding principles for enhancing biological control by modifying the rice landscape have been systematized in the ecologically grounded disciplines of landscape ecology (Forman 1995, Turner and Gardner 1991) and conservation biology (Meffe and Carroll 1994). Landscape ecology emphasizes the study of interactions and exchanges across boundaries within landscapes, the effects of spatial heterogeneity on biotic and abiotic processes, and strategies for managing and enhancing spatial heterogeneity (Turner and Gardner 1991). Using their newly developed analytical tools, landscape ecologists have shown that landscapes exhibit repeated patterns in urban, agricultural, and natural ecosystems and that landscape boundaries exert significant filter effects on energy, nutrients, and biodiversity locally, regionally, and globally (Wiens et al 1985, Holland et al 1991).

Conservation biology seeks to conserve biodiversity, natural ecosystems, and biological processes to better understand the idiosyncrasies of ecological systems (Soule 1986). Conservation biologists have shown 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 water erosion (Meffe and Carroll 1994).

Landscape ecology, conservation biology, and tropical rice management overlap in several key features that form a natural marriage of guiding principles and methods for conserving, enhancing, and sustaining biological control agents in rice ecosystems through landscape modification. Some practical questions for future studies of rice landscapes include the following:

1. What roles do bunds and bordering vegetation play as sinks or sources for pest and natural enemy populations during growing and fallow seasons?
2. What patterns of spatial distribution do pest and natural enemy populations show in population abundance between rice and nonrice habitats, within rice fields, and between the edges and interiors of single rice fields?
3. Can weeds function as natural enemy refuges and, if so, is selective weeding a management option?
4. What effect, if any, does field shape or size have on invertebrate community structure and crop yield?
5. What effect, if any, do different cultivars or varietal mixes have on herbivore–natural enemy interactions?

## Methods for studying spatial features of rice landscapes

Research questions that focus on spatial variation provide a practical framework for (1) investigating the effects of human-imposed boundaries (e.g., roads, bunds, coconut gardens) on the invertebrate population and community structure, (2) analyzing fine-scale pest-natural enemy movements and their associations with weed and disease populations in rice and nonrice habitats, and (3) tracking local pest and disease outbreaks.

Gradient-directed transects (or gradsects) are a useful survey tool (Gillison and Brewer 1985) for analyzing quantitative changes in invertebrate abundance, identifying biotic boundaries (McCoy et al 1986), and assessing invertebrate-vegetation associations in rice and nonrice habitats. Preliminary IRRI results show that herbivores, predators, and parasites assort themselves in nonrandom ways across rice landscapes, with parasitoids displaying an early season preference for bordering nonrice vegetation (Schoenly, unpublished data).

## Pesticide effects on rice-invertebrate communities

In 1988, worldwide sales of rice pesticides reached $2.4 billion, sufficient to nudge out maize and cotton as the single most important crop for pesticides; 90% of this market was located in Asia (Woodburn 1990). Rice pesticides (insecticides, herbicides, molluscicides, fungicides)—irrespective of their targeted action, active ingredient, and timing of application or dosage—will affect the canopy, neustonic, and aquatic fauna in functionally different ways because of species-specific differences in chemical tolerance, habitat association, and feeding position in the food web. An insecticide, for example, may be more toxic to the neustonic fauna than to targeted elements of the canopy fauna (such as leaffolders) because the air-water boundary concentrates insecticide toxicity (Settle et al 1996). If other pesticides act similarly, then the neustonic fauna may be the rice ecologist's "sentinel taxa" for forecasting impending deleterious effects on the rice biota as a whole.

Schoenly et al (1996a) used a food web analysis to examine community-wide effects of insecticides on arthropod populations in Philippine rice fields. In this study, one plot was treated with deltamethrin (a pyrethroid) following conventional practices of Filipino farmers, while another plot received no insecticides. The effect of deltamethrin brought two ecological costs to the farmer—reduced abundance of many natural enemies and a fourfold increase in herbivore populations. The mean chain length of the food web also decreased in the sprayed plot and signaled losses (through emigration and the direct killing action of deltamethrin) of general and specific predators. The time series of samples suggested that nearly 1 mo was required for the sprayed plot to recover following a triple application of deltamethrin. Aside from the additional economic costs to the farmer, insecticides had a negative effect on nontarget beneficial organisms, to the (probable) detriment of rice yields.

Settle et al (1996) used insecticides to demonstrate a link between early season natural enemy populations and late-season pest populations in Indonesian rice fields. Insecticides depressed natural enemy populations and caused pest populations to resurge, particularly rice brown planthoppers. By the season's end, sprayed fields had higher predator populations than untreated fields, but rebounding populations only partly overlapped the hump of extra herbivores sampled earlier in the season, as shown in the Schoenly et al (1996a) study.

Despite increased awareness of pesticide effects on nontarget organisms and human health (Pingali and Roger 1995), pesticide use is likely to increase in tropical Asia by the year 2025. Projections indicate that labor shortages will compel rice farmers to substitute broadcast seeding for traditional transplanting, a change in practice that will stimulate higher herbicide inputs for early season weed control. The eventual spread of the golden apple snail (*Pornacea* spp.) into most of Southeast Asia will stimulate the development and use of new molluscicides for snail control. These additional chemical inputs will likely affect nontarget species in ways similar to those of insecticides, by disrupting biocontrol linkages and reshaping the food web. Ecological and agronomic approaches that seek to measure and mitigate such effects on rice culture and human health will require greater cooperation of agricultural and health professionals in the future.

## Richness and functional diversity of microbial populations and habitats in rice systems

### Microbial richness and diversity of rice-disease populations

Disease organisms can destabilize a system of sustainable rice production. Current disease management practices are largely based on varietal resistance (limited to a few diseases), cultural control, or chemical control (limited to a few countries). In intensive rice production systems like those in China, Korea, Japan, and Vietnam, disease control has largely depended on chemical control. Although chemicals produce immediate effects, they often adversely change the environments where rice is produced. The development of fungicide-resistant strains of pathogens has been reported in areas where these chemicals are intensively used to control diseases (Mew 1990). As we have learned in recent years (Mew and Rosales 1986, 1992), rice ecosystems support abundant populations of microbial antagonists, many of which have the ability to suppress a broad range of plant diseases. Numerous rice diseases are associated with intensive rice production systems, but the occurrence of relatively fewer disease epidemics in tropical ecosystems suggests that indigenous microbial antagonists play a key role in suppressing disease development. Therefore, research on the enhancement of resident biological control agents should advance the management of rice diseases without the need for chemicals.

Assessments of microbial diversity indicate that microorganisms are rich in biocontrol agents in both temperate and tropical environments. When tested against individual fungal pathogens of rice, biocontrol agents obtained from various sources within rice ecosystems do not show a high level of antagonism; how these agents function collectively within rice ecosystems remains to be defined. Approximately 90% of the cultivable bacterial taxa associated with rice ecosystems appear to be nonpathogens with an unknown function, whereas 6% are antagonists to one or more rice fungal pathogens tested, and 4% are pathogens of rice. In addition to a few well-established bacterial antagonists, such as *Pseudomonas putida, Burkholderia cepacia, P. fluorescens,* and *Bacillus subtilis,* a large number of unidentified antagonists exist (Rosales et al 1993). Based on rice seed germination tests, these antagonists are subdivided into three groups: those that promote seed germination and enhance seedling vigor, those that have no effect on seed germination, and those that are harmful and inhibit seed germination. Rice seed carries a large number of bacteria and, whereas most of them are nonpathogens, approximately 10% are pathogenic to rice and 20% are antagonistic to fungal plant pathogens (Cottyn et al 1996, Xie and Mew, unpublished data). Of 57 species identified on rice seed, 27 belong to genus *Pseudomonas* and the remaining 30 belong to another 20 bacterial genera (Xie and Mew, unpublished data). The distribution, population density, and frequency of these groups of bacteria are strongly influenced by seed health status. Pathogens were isolated more frequently from discolored seed than healthy seed. Evidently these indigenous microorganisms, especially those with biological control capability, are an important component of the internal resources of rice ecosystems. These resources are likely to be renewable, with long-term effects on the sustainability of rice production systems, and they should be explored as a means to manage diseases without the need for inputs of additional external resources (such as fertilizer and pesticides).

Should we need a one-time introduction or augmentation of naturally occurring biocontrol agents, an essential screening strategy will be needed whereby strains adaptable to specific habitats and environments are identified and selected. An understanding of the diversity, population density, and distribution of biocontrol agents is vital to the success of biological control. Microbial biocontrol is often crop- and site-specific; thus, the real potential for its control of plant diseases may well lie in the use of many different locally adapted strains for each disease and possibly for different sites with the same crop (Cook 1993). Unlike natural enemies for biological control of rice insect pests, there is little or no established trophic relationship between biocontrol agents and disease pathogens. The tropical rice ecosystem appears to be an ideal system where biocontrol agents can establish and function because of the relatively high humidity, free moisture, and temperature in the rice canopy. Until now, we have depended heavily on host-plant resistance to keep a few diseases in check. It is vital that we also capitalize on naturally occurring biocontrol agents, part of the internal resources of rice ecosytems, to manage some rice diseases, among them sheath blight, one of the most important. Our challenge is to have a good understanding of the relationship of biocontrol agents to microbial communities, and to find ways to enhance the efficiency of the internal linkages of biocontrol agents within those communities for sustainable disease management.

### Biodiversity in rice soils: a separate concept for biocatalytic functions

Microbial populations are the biocatalytic driving force behind bioelement recycling and nutrient supply to crops. Numerous examples exist of close metabolic linkages of microbial populations in natural environments. Complementary pairs of biogeochemical functions (such as nitrification/denitrification, sulfide oxidation/sulfate reduction, or interspecies hydrogen transfer in anoxic waterlogged soils) are a few of the most conspicuous examples (Achtnich et al 1995). Removing the carrier of one function may endanger the stability of the entire network of indispensable biogeochemical functions, unless sufficient redundancy is provided through different carriers of the same metabolic function. Increased richness and redundancy of metabolic functions within certain "energy channels" of a soil microbial community indicate a high degree of environmental stability and resilience.

Early concepts linking environmental stability with species diversity have been refined, with the result being that the level of metabolic functions within soil microbial communities has been downgraded from entire communities to resource compartments (Beare et al 1995, Moore and de Ruiter 1997). The latter are thought to be composed of "guilds," that is, physiologically defined groups of biocatalysts that are linked through energy channels (Moore and de Ruiter 1997, Reichardt, in preparation).

As biodiversity concepts become increasingly adopted by microbial ecologists, microbial diversity is likewise being recognized in agriculture. As an "unseen national and international resource," microbial diversity is believed to deserve greater attention (Hawksworth 1991, Allsopp et al 1995). From molecular genetic fingerprints of prokaryotic genomes in DNA extracted from soil samples, we already know that cultivation can drastically reduce the number of prokaryotic genomes in farmed compared with fallow fields (Torsvik et al 1990, 1994). We cannot yet tell whether the most intensively farmed tropical wetlands show reduced soil-microbial genome diversity.

Intensified agroecosystems contain a number of extremely different subhabitats and niches such as:

1. A subsurface bulk soil that stays submerged and anoxic for most of the cropping period.
2. Aerated habitats in the top layer, an oxygenated microenvironment surrounding the roots, and aerated surfaces of bioturbate structures in subsurface soil.
3. Steep redox potential gradients within the bulk soil as a result of (2).
4. Temporarily dried-out soil layers after preharvest drainage.
5. A floodwater system with successions of algal blooms fueling food webs in water and soil.

Hardly any agroecosystem could be more compartmentalized (Reichardt et al 1996).

Although microbial genome diversity is severely reduced in less complex agricultural systems, its linkage to crop productivity and sustainability remains to be established and specified. Furthermore, we can speculate that complex, integrated soil-floodwater systems could be more durable than aerated agricultural soils. Periodically changing environmental conditions tend to confer maximum levels of resilience and productivity on tidal wetland ecosystems, which show a comparable degree of compartmentalization into different subhabitats of space and time. That might also explain why lowland rice systems could remain sustainable for millennia (Chang 1976).

Because of the dynamic interactions between diverse subhabitats, the question arises whether a high degree of microbial diversity is still required to keep the lowland rice system sustainable. Current concepts of microbial diversity have been adopted from ecologists dealing with macroorganisms (Odum 1971, Reichardt 1995). Critics have already noted that microbial populations cope in a different way with environmental stress than macroorganisms (Brock 1987)—for microorganisms can actively change their environment. Another criticism of applying macroorganism-based biodiversity concepts to microbiota relates to the definition and interpretation of functional redundancy in microbial communities. The coincidence and linkage of single metabolic functions with many other functions in the same cell seem to be ignored (SES 1993).

Despite these conceptual flaws, it is thought that studying microbial functions, including their diversity and distribution in the microbial populations of an agroecosystem, will provide the insight required to judge the strength and resilience of the network of biogeochemical catalysts (Atlas 1984, Zak et al 1994). Practical tools to assess the functional richness of soil microbiota have been developed. Using these tools has widened the scope of microbial diversity assessment. Molecular genetic approaches do not provide us with clues about the expression of genetically encoded functions in a given environment. On the other hand, the conventional assessment of physiologically defined functional groups (guilds) can reflect the diversity of biocatalytic functions that play a role in soil nutrient cycling (Bochner and Savageau 1977, Zak et al 1994, Haack et al 1995). Furthermore, the existence of chemical fingerprints can be exploited to detect and quantify the presence of certain physiological groups of microorganisms (Tunlid and White 1992, Reichardt et al 1997). Although systematic investigations of microbial diversity in lowland rice systems have yet to be undertaken, preliminary investigations indicate distinctly different patterns of functional microbial diversity in rice fields that receive different treatments (Reichardt, in preparation).

## References


Achtnich C, Bak F, Conrad R. 1995. Competition for electron donors among nitrate reducers, ferric iron reducers, sulfate reducers, and methanogens in anoxic paddy soil. Biol. Fertil. Soils 19:65-72.

Allen TFH, Starr TB. 1982. Hierarchy: perspectives for ecological complexity. Chicago, I11. (USA): University of Chicago Press. 310 p.

Allsopp D, Colwell RR, Hawksworth DL. 1995. Microbial diversity and ecosystem function. Wallingford (UK): CAB International.

Atlas RM. 1984. Use of microbial diversity measurements to assess environmental stress. In: Klug JM, Reddy CA, editors. Perspectives in microbial ecology. p 540-545.

Barrion AT, Litsinger JA. 1995. Riceland spiders of South and Southeast Asia. Wallingford (UK): CAB International and the International Rice Research Institute. 700 p.

Beare MH, Coleman DC, Crossley DA, Hendrix PF, Odum EP. 1995. A hierarchical approach to evaluating the significance of soil biodiversity to biogeochemical cycling. Plant Soil 170:5-22.

Bell SS, McCoy ED, Mushinsky HR. 1991. Habitat structure: the physical arrangement of objects in space. New York (USA): Chapman and Hall. 438 p.

Bochner BR, Savageau MA. 1977. Generalized indicator plate for genetic, metabolic, and taxonomic studies with microorganisms. Appl. Environ. Microbiol. 33:434-444.

Brock TD. 1987. The study of microorganisms in situ: progress and problems. In: Fletcher M, Gray TRG, Jones JG, editors. Ecology of microbial communities. Cambridge (UK): Cambridge University Press.

Catling D. 1992. Rice in deepwater. Manila (Philippines): International Rice Research Institute.

Chang TT. 1976. The origin, evolution, cultivation, dissemination, and diversification of Asian and African rices. Euphytica 25:425-441.

Cohen JE, Schoenly KG, Heong KL, Justo H, Arida G, Barrion AT, Litsinger JA. 1994. A food-web approach to evaluating the impact of insecticide spraying on insect pest population dynamics in a Philippine irrigated rice ecosystem. J. Appl. Ecol. 31:747-763.

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

Cottyn B, Cerez MT, van Outryve MF, Barroga J, Swings J, Mew TW. 1996. Bacterial diseases of rice. I. Pathogenic bacteria associated with sheath rot complex and grain discoloration of rice in the Philippines. Plant Dis. 80:429-437.

de Kraker J. 1995. Impact of natural enemies on rice leaffolders. PhD thesis. Wageningen Agricultural University. The Netherlands.

Forman RTT. 1995. Land mosaics: the ecology of landscapes and regions. Cambridge (UK): Cambridge University Press. 632 p.

Gillison AN, Brewer KRW. 1985. The use of gradient-directed transects or gradsects in natural resource surveys. J. Environ. Manage. 20:103-127.

Haack SK, Garchow H, Klug MJ, Forney LJ. 1995. Analysis of factors affecting the accuracy, reproducibility, and interpretation of microbial community carbon source utilization patterns. Appl. Environ. Microbiol. 61:1458-1468.

Hawksworth DL, editor. 1991. The biodiversity of microorganisms and invertebrates: its role in sustainable agriculture. Wallingford (UK): CAB International. 302 p.

Heckman CW. 1979. Ricefield ecology in northeastern Thailand: the effect of wet and dry seasons on a cultivated aquatic ecosystem. Monogr. Biol. 34:l-22.

Heong KL, Aquino GB, Barrion AT. 1991. Arthropod community structures of rice ecosystems in the Philippines. Bull. Entomol. Res. 81:407-416.

Heong KL, Aquino GB, Barrion AT. 1992. Population dynamics of plant- and leafhoppers and their natural enemies in rice ecosystems in the Philippines. Crop Prot. 11:371-379.

Heong KL. 1996. Pest management in tropical rice ecosystems: new paradigms for research. In: Hokyo N, Norton G, editors. Pest management strategies in Asian monsoon agroecosystems. Proceedings of an International Workshop, 15-18 Nov 1995, Kumamoto, Japan. Japan: Kyushu National Agricultural Experiment Station, Ministry of Agriculture, Forestry and Fisheries. p. 139-154.

Holland MM, Risser PG, Naiman RJ, editors. 1991. Ecotones: the role of landscape boundaries in the management and restoration of changing environments. New York (USA): Chapman and Hall. 142 p.

Hubbell SP, Foster RB. 1986. Biology, chance, and history and the structure of tropical rain forest tree communities. In: Diamond J, Case TJ, editors. Community ecology. New York (USA): Harper and Row. p. 314-329.

Ludwig JA, Reynolds JF. 1988. Statistical ecology. A primer on methods and computing. New York (USA): John Wiley and Sons. 337 p.

McCoy ED, Bell SS, Walters K. 1986. Identifying biotic boundaries along environmental gradients. Ecology 67:749-759.

McGowan JA, Walker PW. 1993. Pelagic diversity patterns. In: Ricklefs RE, Schluter D, editors. Species diversity in ecological communities: historical and geographical perspectives. Chicago (USA): University of Chicago Press. p. 203-214.

Manly BFJ. 1991. Randomization and Monte Carlo methods in biology. London (UK): Chapman and Hall. 281 p.

Meffe GK, Carroll CR. 1994. Principles of conservation biology. Sunderland, Mass. (USA): Sinauer Associates, Inc. 600 p.

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

Mew TW. 1990. Disease management in rice. In: Handbook of pest management in agriculture. Vol. III. Boston (USA): CRC Press. p. 279-299.

Mew TW, Rosales AM. 1992. Control of *Rhizoctonia* sheath blight and other diseases of rice by seed bacterization. In: Tjamos ES et al, editors. Biological control of plant diseases. New York (USA): Plenum Press. p. 113-123.

Moore JC, de Ruiter PC. 1997. Compartmentalization of resource utilization within soil ecosystems. In: Gange AC, Brown VK, editors. Multitrophic interactions in terrestrial systems. Blackwell. p 375-393.

Myers AA, Giller PS, editors. 1988. Analytical biogeography. New York (USA): Chapman and Hall. 578 p.

Odum EP. 1971. Fundamentals of ecology. Third edition. Philadelphia (USA): W.B. Saunders.

O'Neill RV, De Angelis DL, Waide JB, Allen TFH. 1986. A hierarchical concept of ecosystems. Monographs in Population Biology 23. Princeton, N.J. (USA): Princeton University Press. 253 p.

Ooi PAC. 1996. Experiences in educating rice farmers to understand biological control. Entomophaga 41:375-385.

Pingali PL, Roger PA. 1995. Impact of pesticides on farmer health and the rice environment. Boston (USA): Kluwer Academic Publishers. 664 p.

Polhemus JT, Reisen WK. 1976. Aquatic hemiptera of the Philippines. Philip. J. Biol. 5:259-294.

Reichardt W. 1995. Microbes as a challenge to concepts of marine ecosystem analysis. Helgolander Meeresunters 49:135-141.

Reichardt W, Mascarina G, Padre B, Doll J. 1997. Microbial communities of continuously cropped, irrigated rice fields. Appl. Environ. Microbiol. 63:233-238.

Reichardt W, Briones A, Padre B, de Jesus R, Mascarina G. 1996. Dynamics of soil microbial communities and sustainable nutrient supply in highly intensified rice cultivation. In: Attanandana T, Kheoruenromne I, Pongsakul P, Vearasilp T, editors. Maximizing sustainable rice yields through improved soil and environmental management. Proceedings of International Symposium, Khon Kaen, Thailand. p 887-896.

Roger PA, Heong KL, Teng PS. 1991. Biodiversity and sustainability of wetland rice production: role and potential of microorganisms and invertebrates. In: Hawksworth DL, editor. The biodiversity of microorganisms and invertebrates: its role in sustainable agriculture. Wallingford (UK): CAB International. p 117-136.

Rosales AM, Vantomme R, Swings J, De Ley J, Mew TW. 1993. Identification of some bacteria from paddy antagonistic to several rice fungal pathogens. J. Phytopathol. 138:189-202.

Schoenly KG, Cohen JE, Heong KL, Arida AS, Barrion AT, Litsinger JA. 1996a. Quantifying the impact of insecticides on food web structure of rice-arthropod populations in a Philippine farmer's irrigated field: a case study. In: Polis G, Winemiller K, editors. Food webs: integration of patterns and dynamics. New York (USA): Chapman and Hall. p 343-351.

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

Schoenly KG, Justo HD, Banin AT, Harris MK, Bottrell DG. 1998. An analysis of invertebrate agrobiodiversity in a Philippine farmer's irrigated rice field. Environ. Entomol. (In press.)

SES (Soil Ecology Society, USA). 1993. The functional significance and regulation of soil biodiversity. Executive Summary of SES Conference at Michigan State University, 3-8 May 1993. p 1-10,

Settle WH, Ariawan H, Tri Astuti E, Cahyana W, Hakirn AL, Hindayana D, Sri Lestari A, Pajarningsih, Sartanto. 1996. Managing tropical rice pests through conservation of generalist natural enemies and alternate prey. Ecology 77:1975-1988.

Simpson IC, Roger PA, Oficial R, Grant IF. 1993. Density and composition of aquatic oligochaete populations in different farmers' ricefields. Biol. Fertil. Soils 16:27-33.

Soule ME. 1986. Conservation biology: the science of scarcity and diversity. Sunderland, Mass. (USA): Sinauer Associates. 584 p.

Strong DR Jr, Simberloff D, Abele LG, Thistle AB. 1984. Ecological communities: conceptual issues and the evidence. Princeton, N.J. (USA): Princeton University Press. 613 p.

Torsvik V, Salte K, Sorheim R, Goksoyr J. 1990. Comparison of phenotypic diversity and DNA heterogeneity in a population of soil bacteria. Appl. Environ. Microbiol. 56:776-781.

Torsvik V, Goksoyr J, Daae F.L, Sorheim R, Michalsen J, Salte K. 1994. Use of DNA analysis to determine the diversity of microbial communities. In: Ritz K et al, editors. British Society of Soil Science. p 39-48.

Tunlid A, White DC. 1992. Biochemical analysis of biomass, community structure, nutritional status, and metabolic activity of microbial communities in soil. In: Stotzky G, Bollag JM, editors. Soil biochemistry. Vol. 7. New York (USA): Marcel Dekker. p 229-262.

Turner MG, Gardner RH, editors. 1991. Quantitative methods in landscape ecology. New York (USA): Springer-Verlag. 536 p.

Weinberg GM. 1975. An introduction to general systems thinking. New York (USA): John Wiley and Sons. 279 p.

Whittaker RH. 1975. Communities and ecosystems. Second edition. New York (USA): MacMillan Publishing. 385 p.

Wiens JA, Crawford CS, Gosz JR. 1985. Boundary dynamics: a conceptual framework for studying landscape ecosystems. Oikos 45:421-427.

Woodburn AT. 1990. The current rice agrochemicals market. In: Grayson BT, Green MB, Copping LG, editors. Pest management in rice. New York (USA): Elsevier Applied Science. p 15-30.

Yano K, Miyamoto S, Gabriel BP. 1981. Faunal and semiaquatic Heteroptera from the Philippines. Esakia 16:5-32.

Yano K, Miyamoto S, Chu YI. 1982. Faunal and biological studies on the insects of paddy fields in Asia. VI. Preliminary report on the aquatic and semiaquatic Heteroptera from Taiwan. Chin. J. Entomol. 2:l-13.

Zak JC, Willig MR, Moorhead DL, Wildman HG. 1994. Functional diversity of microbial communities: a quantitative approach. Soil Biol. Biochem. 26:1101-1108.

## Notes

*Authors' address:* International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines. k.schoenly@cgnet.com t.mew@cgnet.com w.reichardt@cgnet.com

*Acknowledgments:* The authors thank K.S. Fischer, D.A. Fuccillo, M.K. Harris, and M. Mazzala for their helpful suggestions and technical comments.

*Citation:* Dowling NG, Greenfield SM, Fischer KS, editors. 1998. Sustainability of rice in the global food system. Davis, Calif. (USA): Pacific Basin Study Center, and Manila (Philippines): International Rice Research Institute.

# Part V:
# Economic Considerations

CHAPTER 18

# The economic value of genetic improvement in rice

R.E. Evenson

Rice productivity increased dramatically during the Green Revolution of the late 1960s. A number of factors contributed to this increase, such as expansions in multiple cropping, irrigation, and input use. Genetic improvement in the form of modern, high-yielding rice varieties contributed productivity gains as well. These genetic improvements often enabled and complemented other productivity-enhancing activities.

This paper reviews data on varietal releases from approximately 100 rice breeding programs from 1965 to 1990. The data showed that IRRI aided genetic improvement both directly by making crosses leading to released varieties and indirectly through parental, grandparental, and other ancestral contributions to the genealogies of released rice varieties. The International Network for Genetic Evaluation of Rice—INGER—facilitates the international exchange of genetic resources.

Studies of the value added by genetic improvement are reviewed. Several studies measured yield increases associated with specific genetic traits incorporated into rice varieties. One study measured the contribution of genetic traits to the expansion of the area planted to modern varieties. Studies of returns to rice research also showed that genetic improvement was the major source of gains in rice productivity during the Green Revolution. Another study addresses prospects for further genetic gains.

Rice production has increased at historically unprecedented rates in the post–World War II decades. This growth was driven by and required by historically unprecedented increases in population. It is a remarkable achievement that rice production per capita for the large population for which rice is the staple food has increased over this period. It is perhaps more remarkable that this major expansion in production has occurred with little expansion in land devoted to rice. Rice productivity, that is, production per unit of land (and other inputs), has increased to enable this accomplishment during what is now termed the "First Green Revolution" (of the late 1960s). Population growth, while having slowed in most countries in the developing world, will nonetheless continue at high rates for several more decades. This will call for a "Second Green Revolution" if production per capita is to be maintained. Genetic improvement in rice has been an important (though not the only) component of (source of) productivity growth in the First Green Revolution. In this paper, I review the role of genetic improvement in the First Green Revolution and assess the prospects for genetic improvement with new tools for biotechnology research in the Second Green

Revolution. First, I review the major features of genetic improvement in rice. Second, I review studies that attempt to value rice genetic resources. Third, I review studies of returns to rice research and assess the comparative role of genetic improvement and other productivity-enhancing activities (better crop management practices, better market infrastructure, etc.). Fourth, I assess the prospects for genetic improvement in the Second Green Revolution using the experience to date of the Rice Biotechnology Program, in operation since 1985.

## Genetic resources and rice breeding programs[1]

Genetic resources in the form of original landraces, wild species, and related materials have been exchanged freely and readily between breeders at the International Rice Research Institute (IRRI) and in national agricultural research systems (NARS). The International Rice Germplasm Collection (IRGC) is a large collection that includes duplicates of materials in national rice germplasm collections (NRGCs). Much of the IRGC has been evaluated for agronomic traits, and this information and the genetic resources themselves have been readily available to rice breeders in NARS.

Advanced genetic resources are also exchanged internationally. These materials consist of advanced breeding lines and varieties (the descendants of original landraces, which have been crossed and recrossed for many generations). Some of this germplasm is exchanged under the aegis of the IRGC and NRGCs. The development in 1975 of the International Network for Genetic Evaluation of Rice (INGER), a system of specialized rice nurseries, provided a vehicle for exchanging as well as evaluating advanced genetic resources.

Evenson and Gollin (1997) studied releases of indica and japonica rice varieties from 1962 to 1991. A total of 1,741 releases were classified according to the releasing country and release date. The genealogies (parentage) of each release were analyzed, which enabled breeding strategies and the landrace complexities of these releases to be characterized further.

Table 1 summarizes these varieties by releasing country. Note that IRRI made a number of the crosses from which these varieties were selected, but officially released only a few varieties. India, with 26 rice breeding programs, led all countries in number of releases (643). Varieties from more than 100 breeding programs were released. Approximately 20 varieties were released each year in the early Green Revolution period; this number rose to nearly 80 per year in 1976-80 and has remained steady at around 75 per year since.

Table 2 provides an indication of the scope of the international exchange of varieties by comparing the location of the breeding program where a cross was made with the location of the program that released varieties based on that cross. Panel I of Table

---

[1] This section is based on Evenson (1998c).

**Table 1. Numbers of varieties included in the data set by country of release and time period of release.**

| Country/region | Pre-1965 | 1966-70 | 1971-75 | 1976—80 | 1981-82 | 1986-91 | Total |
|---|---|---|---|---|---|---|---|
| Africa | 3 | 7 | 8 | 17 | 26 | 42 | 103 |
| Bangladesh | 1 | 7 | 8 | 11 | 4 | 33 | 64 |
| China | 0 | 1 | 8 | 30 | 31 | 12 | 82 |
| India | 10 | 67 | 136 | 139 | 125 | 166 | 643 |
| Indonesia | 1 | 2 | 5 | 21 | 10 | 9 | 48 |
| Korea | 0 | 5 | 11 | 35 | 40 | 15 | 106 |
| Latin America | 7 | 9 | 48 | 32 | 43 | 100 | 239 |
| Myanmar | 0 | 4 | 6 | 21 | 37 | 8 | 76 |
| Nepal | 0 | 0 | 1 | 10 | 4 | 2 | 17 |
| Oceania | 0 | 1 | 4 | 1 | 0 | 0 | 6 |
| Pakistan | 0 | 4 | 2 | 3 | 3 | 0 | 12 |
| Philippines | 3 | 4 | 13 | 23 | 8 | 2 | 53 |
| Sri Lanka | 3 | 14 | 4 | 8 | 21 | 3 | 53 |
| Taiwan | 0 | 3 | 0 | 3 | 0 | 0 | 6 |
| Thailand | 1 | 2 | 4 | 8 | 5 | 3 | 23 |
| USA | 2 | 5 | 18 | 17 | 3 | 6 | 51 |
| Vietnam | 0 | 16 | 6 | 16 | 16 | 5 | 59 |
| Other Southeast Asia | 2 | 1 | 8 | 7 | 6 | 5 | 29 |
| Other | 0 | 7 | 15 | 15 | 15 | 19 | 71 |
| Total | 33 | 159 | 305 | 417 | 397 | 430 | 1,741 |

**Table 2. International flows of genetic resources by time period.**

| | Pre-1965 | 1966-70 | 1971-75 | 1976—80 | 1981-85 | 1986-91 | Total |
|---|---|---|---|---|---|---|---|
| I. Released varieties, percentage based on | | | | | | | |
| IRRI cross | 3 | 25 | 19 | 22 | 18 | 12 | 17 |
| (through INGER) | (0) | (0) | (2) | (13) | (14) | (11) | (8) |
| Other NARS cross | 16 | 7 | 6 | 6 | 6 | 5 | 6 |
| (through INGER) | (0) | (0) | (0) | (2) | (4) | (3) | (3) |
| Own NARS cross | 81 | 68 | 75 | 72 | 76 | 83 | 77 |
| II. Parents (%) of released varieties with one or more parents | | | | | | | |
| IRRI cross | 0 | 24 | 29 | 33 | 23 | 19 | 24 |
| (through INGER) | (0) | (0) | (0) | (9) | (20) | (15) | (10) |
| Other NARS cross | 27 | 25 | 21 | 15 | 18 | 20 | 18 |
| (through INGER) | (7) | (2) | (5) | (9) | (15) | (15) | (10) |
| Own NARS cross | 73 | 51 | 50 | 52 | 59 | 61 | 58 |
| III. Frequency (%) of parental crosses with no foreign genetic resources | | | | | | | |
| All NARS parents | 24 | 11 | 8 | 6 | 7 | 10 | 8 |

Table continued

**Table 2. continued.**

| | Pre-1965 | 1966-70 | 1971-75 | 1976-80 | 1981-85 | 1986-91 | Total |
|---|---|---|---|---|---|---|---|
| IV. Landrace content of released varieties greater than | | | | | | | |
| 4 | 10 | 31 | 47 | 67 | 62 | 56 | 55 |
| 9 | | 03 | 13 | 39 | 34 | 32 | 27 |
| 15 | 8 | 0 | 3 | 21 | 18 | 18 | 14 |
| Average number of landraces | 2.55 | 4.01 | 5.29 | 8.15 | 7.49 | 7.23 | |
| From IRRI (%) | 3 | 3 | 59 | 79 | 74 | 70 | 68 |
| V. Landrace introduction | | | | | | | |
| Number from IRRI | 0 | 16 | 14 | 21 | 11 | 13 | 75 |
| Number from NARS | 21 | 87 | 126 | 146 | 171 | 180 | 731 |

2 shows that IRRI was an important producer of the crosses from which releases were subsequently made. In the early Green Revolution period, 1966-70, IRRI made 25% of all crosses leading to varieties. This percentage has declined to 12 in the most recent period, but IRRI's plant breeding program remains a potent contributor to varietal development. Table 2 also reports instances in which the releasing unit first obtained a cross via an INGER nursery.

Table 2 summarizes comparable data for varietal parents (see panel II). Here we see that IRRI produced the crosses from which 24% of varietal parents were selected. Other NARS produced the crosses from which an additional 18% of varietal parents were selected. By the 1980s, INGER was the source for 80% of IRRI-based parents and more than half of NARS-based parents.

The importance of international exchanges in rice breeding is shown by the relatively low percentage of varietal releases for which all parental material came from national sources (most of these releases were made in India, see panel III, Table 2).

The landrace content of released varieties has increased: the average number of landraces in a given release has risen from under 3 to around 8, although some recently released varieties contain more than 25 landraces in their genealogies (panel IV, Table 2). More than 70% of these landraces were brought into the genealogies through an IRRI ancestor.

Panel V of Table 2 shows another dimension of IRRI's role in breeding by reporting the number of new landraces introduced into the landrace pool by period and by originating source. Here we note first that genetic resources consisting of an impressive number of new landraces (and one or two wild species) have been introduced into the pool of successful varieties. The fact that the 1,741 releases included 838 landraces that were not contained in the landrace pool prior to 1965 shows that genetic resource collections have been valuable to breeding programs.

Second, the data in panel V reveal that IRRI has actually introduced very few landraces into the pool. Only 80 of the 838 new landraces were introduced via IRRI crosses. By contrast, of the landraces in released varieties, roughly 70% were introduced via an IRRI cross. This is the result of two factors. First, IRRI's powerful breeding lines incorporate many landraces that were first brought in through a NARS cross. Second, the widespread use of IRRI crosses as breeding lines multiplies the use of the landraces they contain.

Collin and Evenson (1993) have noted that a small set of landraces was built into IRRI breeding lines possessing the original semidwarf plant design. To date, these lines have served as the basis for much of the varietal development research described here. IRRI, which had excellent access to genetic resources, did not invest heavily in efforts to exploit more landraces and was not highly successful in doing so, partly because the combinability and use of new landraces was limited by the "narrowness" of the original plant design. The NARS, even though they had poorer access to genetic resource collections, had somewhat broader plant design bases and were somewhat more diligent in searching for landrace-based traits. IRRI, on the other hand, devoted much of its effort to packaging high-powered breeding lines using NARS-developed materials and often using INGER to provide access to those lines.

Collin and Evenson (1993) have traced the routes by which varieties were released (Table 3). These routes are defined as mutually exclusive categories, so each variety in the data set falls into exactly one of 13 categories (see box). (These route

**Routes of varietal release**

**Borrowed varieties**

1. IRRI line, borrowed through INGER (IRRI/INGER).
2. IRRI line, borrowed independently of INGER (IRRI/no INGER).
3. Varietyfrom another national program, borrowed through INGER (other national/INGER).
4. Variety from another national program, independently of INGER (other national/national/no INGER).

**Nationally developed varieties, borrowed parents**

5. At least one parent from IRRI, borrowed through INGER (IRRI parent/INGER).
6. At least one parent from IRRI, borrowed independently of INGER (IRRI parent/no INGER).
7. No IRRI parents, but at least one parent borrowed from another national program via INGER (other national parent/INGER).
8. No IRRI parents, but at least one parent borrowed from another national program independently of INGER (other national parent/no INGER).

**Nationally developed varieties and parents, borrowed grandparents (other)**

9. At least one grandparent from IRRI, borrowed through INGER (IRRI grandparent/INGER).
10. At least one grandparent from IRRI, borrowed independently of INGER (IRRI grandparent/no INGER).
11. No IRRI grandparents, but at least one grandparent borrowed from another national program via INGER (other national grandparent/INGER).
12. No IRRI grandparents, but at least one grandparent borrowed from another national program independently of INGER (other national grandparent/no INGER).

**Nationally developed varieties, parents, grandparents**

13. All parents and grandparents from country of release (pure national).

**Table 3. Routes of varietal release: descriptive statistics.**

| Route | Varieties No. | Varieties % | Total area (000 ha) | Area (%) | Landraces (av no.) Pre–1976 | Landraces (av no.) Post–1976 | Landraces independent of IRRI (av no.) Pre–1976 | Landraces independent of IRRI (av no.) Post–1976 | Landraces with rare trait index >5.0 (av no.) |
|---|---|---|---|---|---|---|---|---|---|
| IRRI/INGER | 146 | 8.5 | 5,177 | 13.3 | n.a. | 13.2 | n.a. | 0.0 | 12.55 |
| IRRI/no INGER | 148 | 8.7 | 3,959 | 10.2 | 5.4 | 12.4 | 0.0 | 0.0 | 7.66 |
| Other/INGER | 37 | 2.2 | 411 | 1.1 | n.a. | 4.2 | n.a. | 2.1 | 3.35 |
| Other/no INGER | 59 | 3.5 | 2,954 | 7.6 | 4.4 | 5.2 | 2.5 | 1.6 | 4.14 |
| IRRI parent/INGER | 214 | 12.5 | 6,570 | 16.9 | n.a. | 10.4 | n.a. | 1.2 | 9.55 |
| IRRI parent/no INGER | 313 | 18.3 | 5,589 | 14.4 | 5.6 | 9.5 | 1.7 | 1.4 | 6.53 |
| Other parent/INGER | 208 | 12.2 | 4,283 | 11.0 | n.a. | 2.9 | n.a. | 2.5 | 1.52 |
| Other parent/no INGER | 151 | 8.8 | 3,228 | 8.3 | 3.4 | 4.8 | 3.4 | 3.8 | 2.68 |
| IRRI gparent/INGER | 14 | 0.8 | 670 | 1.7 | 0.0 | 7.2 | 0.0 | 3.0 | 6.00 |
| IRRI gparent/no INGER | 94 | 5.5 | 1,436 | 3.7 | 7.4 | 10.7 | 4.6 | 3.6 | 8.93 |
| Other gparent/INGER | 0 | 0.0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 |
| Other gparent/no INGER | 180 | 10.5 | 1,482 | 3.8 | 4.4 | 4.1 | 4.3 | 3.8 | 2.04 |
| Pure national | 145 | 8.5 | 3,121 | 8.0 | 3.2 | 2.6 | 2.7 | 2.2 | 1.10 |

categories were used in the production study on modern varieties reviewed in the next section.)

The data in Table 3 show several additional features of rice varietal development. They show, for example, that whereas IRRI crosses produced 17.2% of the varieties, they were planted on 23.5% of the rice area. Exchanged or borrowed NARS varieties accounted for 5.7% of the varieties but 8.7% of the area.

IRRI varieties, parents, and grandparent materials have the highest landrace content. The "rare trait" index (Gollin and Evenson 1993) is the ratio of landrace content in all ancestors to landrace use in parental crosses. It reflects the breeding strategy of incorporating a landrace to achieve a single trait and replicating that landrace in more broadly used breeding materials. IRRI clearly pursues this strategy to a greater degree than do NARS.

## Studies of the value of genetic resources

The released varieties summarized in Table 1 were produced using the following resources:

1. The stock of genetic resources in collections accessible to breeders.
2. Evaluation information for genetic resources.
3. Prebreeding research designed to produce advanced lines and the evolution of these lines.
4. Breeding at international agricultural research centers and in NARS programs.

5. Field testing and evaluation of new varieties.
6. Farmer testing, evaluation, and adoption.

Three types of studies have been undertaken to place value on these resources; the first are "hedonic trait value" studies. I review four such studies below (three for India, one for Indonesia). The second is a study of the adoption of modern varieties (MV) (in India), in which genetic combination variables are specified as determinants of MV adoption. The third is a study of the determinants of MV production.

### Hedonic trait value studies

The "hedonic" specification is based on the idea that traits incorporated into new rice varieties affect rice yields in farmers' fields. Three such studies have been undertaken for India. An extension of this model, in which crop losses, rice productivity, and insecticides are affected by traits in Indonesia, is also reported.

The statistical model underlying these studies is simple:

$$V_{ij} = F\,(T_{1ij}, \ldots, T_{nij}, Z_j)$$

where $V_{ij}$ is a value indicator (yield, productivity, losses) for variety *i,* location *j;* $T_{1ij}, \ldots, T_{nij}$ are trait content measures for variety *i,* location *j;* and $Z_j$ is a vector of economic, soil, and climatic conditions at location *j.* Trait content variables include insect resistance, disease resistance, ecological stress tolerance (tolerance of flood, drought, etc.), and agronomic (grain) quality. Plant breeders have rated varieties in India and Indonesia according to the presence or absence of these traits.

Gollin and Evenson (1998) reported the first trait value study of this type for rice. The study used data on actual varieties planted in farmers' fields to construct actual proportions of area planted to varieties with particular sets of traits. District rice yields (with some control for prices and input use) were regressed on these proportions for the years for which data were available. The study found that when varieties incorporating tolerance of abiotic stresses and superior agronomic characteristics were made available to farmers, yields were higher. (This was not the case for disease and insect resistance.)

Gollin and Evenson (1998) also found strong positive effects when the number of landraces (from both national and international sources) incorporated in varieties was associated with higher yields. This was evidence of the value of genetic resources, as Gollin and Evenson argued that the size and evaluation status of the germplasm collections enabled more materials possessing rare traits to be built into modern rice varieties.

Two further studies for India (Rao and Evenson 1998) were based on yield data by variety. The first Indian varietal data set was compiled by the Indian Council of Agricultural Research (ICAR) for selected districts and years. The Council reported yields for the three "highest yielding" varieties in farmers' trials in each district/year combination for irrigated and unirrigated *kharif* (summer season) and *rabi* (winter season) rice crops. Fertilizer use was measured and yields reported for a sample of farms in each district. Each variety was assigned trait characteristics (noted by breeders) and yields were related to these characteristics. This data set encompassed the years 1977-89 and covered 45 districts.

The second Indian varietal data set was based on state-level data reported by state departments of agriculture for different years. For each state/year combination, all important varieties planted were included in the data set. Data on yields (from farmers' crop-cut estimates) and area planted were reported. For these data, we can use the yields of other varieties in the state and year as a reference group. Thus, for a given year, yields of varieties with trait *x* can be compared with the yields of all varieties in the state. Problems related to weather, insects. diseases, and so forth were assumed to have affected all varieties equally. Five states were covered: Punjab, Haryana, Andhra Pradesh, Tamil Nadu, and Karnataka. The estimation equation used the standard productivity relationship including research, extension, and infrastructure.

In both data sets, varieties with insect resistance showed better performance in the field, although neither data set showed that resistance to brown planthopper had value. The estimates for disease resistance, on the other hand, were weaker. Both data sets showed yield effects for sheath blight resistance; the state data set showed a blast resistance effect and a positive, nonsignificant effect for rice tungro virus.

Economic calculations using the district data showed a 2% yield gain for disease resistance and 3% for insect resistance. The estimate for varieties at the state level, on the other hand, showed a 4.5% yield gain from disease resistance and a 6.9% yield gain from insect resistance.

The nature of the data argues in favor of the state estimate as the more reliable of the two estimates. Adoption of varieties incorporating the traits mentioned earlier is quite low, with only a few traits covering 20% of the area, at the mean of the data set. By 1997, these adoption levels had become higher by a factor of 1.5 to 2. In India, conventional breeding for disease resistance has produced a 7–10% yield gain, and conventional breeding for insect resistance has produced a gain of 10–14%. Further conventional breeding is likely to increase these levels further—perhaps doubling them in another 20 years.

The Indonesia study (Evenson 1998a) was the first to use crop loss and pesticide use data in a trait value study. It was also the first to use total factor productivity (TFP) at the crop level as a productivity index.

The Indonesian Ministry ofAgriculture measured crop losses by type (insect and disease) for each province and year. Data on varieties planted and trait ratings by variety were also available by province and year. Thus, it was possible to compute the percentage of area planted in each region and period with specific traits. For Indonesia, sufficient data also exist on inputs by crop to enable us to calculate TFP indices that take into account the use of conventionally measured inputs.

Modern rice varieties in Indonesia have undergone considerable change within the MV class. Dwidjono (1993) has defined four "generations" of rice varieties. Generation 1 includes IR5, IR8, IR20, and C4-63, which are the first semidwarf varieties developed in the Philippines (IR5, IR8, and IR20 at IRRI, C4-63 at the University of the Philippines Los Baños). This generation of MVs also includes Pelita 1 and Pelita 2, the first Indonesian-bred varieties. These varieties were generally subject to brown planthopper (BPH) and tungro virus attacks. Generation 2 includes varieties IR22 and IR34 from IRRI as well as several varieties from Indonesian programs, all developed in response to the insect and disease problems afflicting the first generation of MVs (BPH and tungro virus). Generation 3 includes both IRRI (lR32–38)and Indonesian varieties that incorporate multiple resistance and tolerance traits. The IRRI varieties were the result of its Genetic Evaluation Unit (GEU) program in the 1970s. Generation 4 includes other MVs incorporating more location-specific and related traits. These varieties (mostly Indonesian ones) were released in the 1980s.

Plant breeders rated each of these MVs for resistance to three diseases (bacterial leaf blight, tungro virus, and grassy stunt virus) and two insect pests (BPH and gall midge). It was possible to construct a data set for eight regions for 1971-90. The endogenous variables involve each of the five crop-loss variables, pesticide use, and a cumulative index of rice TFP. The pesticide variable was treated as an independent determining variable.

The a priori expectations were that an increase in area planted to varieties resistant to an insect or disease should reduce crop losses. It was also expected that pesticide use would reduce crop losses. Research on rice, holding varietal characteristics constant, is a measure of nonvarietal research findings, and it too is expected to reduce crop losses.

The coefficients for pesticide use were marginally significant and negative only in the case of losses caused by insects. They did not show strong effects for losses caused by disease (except for grassy stunt virus). Varietal resistance traits were also not consistently significant in their effects on losses, with the strongest evidence for a reduction in losses caused by insects. Interestingly, nonvarietal research appeared to have loss-reducing effects for BPH, bacterial leaf blight, and grassy stunt virus. There was also some evidence that larger farms have lower crop losses per hectare for these same pests and diseases.

The chief variable determining TFP growth in rice is the research stock variable, with an additional explanation to be had from the trait and generational variables. When the traits were included, three of the five appear to be significantly positive, and the sum of the five coefficients is positive and approximately equal to one, indicating that a 1% expansion in every trait would produce a 1% expansion in TFP.

The study indicated that if all varieties had resistance to BPH, losses from this pest would be reduced by 2% (of crop yields). Approximately the same could be said for gall midge resistance. In actuality, only 60% of the varieties have BPH resistance and roughly 40% have gall midge resistance.

Thus, by these estimates, actual losses were only about 1% lower because of these two traits. But if we consider other insect pests and a further expansion of trait area, we could conclude that conventional plant breeding has reduced crop losses by 3–5%(considering BPH and gall midge to represent one-third to one-half of all insect problems). There appears to be future potential for another 3–5% reduction if biotechnology methods enable a more complete incorporation of insect resistance traits. For disease resistance traits, the evidence was less clear. Only tungro virus resistance showed an indication of reducing crop losses, and that is only 0.33%. Even with some expansion to other diseases, it is difficult to say that disease resistance has contributed much more than 1% to reducing crop losses to date.

The pesticide use estimates indicated that the total set of traits reduces pesticide use by 20%. This amounts to roughly 1% of crop value.

The TFP-based estimates were higher than the combined crop-loss and pesticide estimates. With an expansion factor to cover other diseases and insects, the TFP evidence suggests that 15% of current TFP levels is the result of disease and insect traits. The generation evidence indicated a 25% gain for generation 3. This is more than double the contributions suggested by the crop-loss and pesticide reduction estimates. These estimates, however, can be reconciled by noting that TFP (yields) may incorporate a synergistic effect (that is, the sum is greater than the parts, and in this case it is greater than the crop-loss pest parts).

It may thus be reasonable to conclude that, to date, rice yields in Indonesia are roughly 15% higher because of improved traits and that, with synergism, they may be 25% higher. It should be noted that this synergism is really the result of quantitative trait improvement. Conventional plant breeding methods have allowed considerable gains to be realized in Indonesia and more are in the offing.

## Modern variety adoption and genetic traits

As in Indonesia, in India the class of MVs has not been static over time, and several generations of varieties, each incorporating new traits, have been produced.

Traits contribute value in two ways. First, they may result in higher rice yields, because of reduced losses from pests and diseases (or they may result in higher value). But they also contribute value if they enable high-yielding varieties to be grown in rice ecologies where they were previously unsuited. In light of the dual nature of trait values (i.e., affecting both yield and MV adoption), a model of MV adoption, supply, and factor demand was developed for India (Evenson 1998b).

The adoption of MVs itself was treated as an endogenous choice variable (previous studies have argued that aggregation alleviates this endogeneity; see Evenson et a1 1996). The logic of the discussion about traits suggests that profitability and the availability of traits, along with farmer characteristics and extension, will govern MV adoption. One of the concerns in this specification was to measure trait availability so as to achieve “exogeneity” for trait availability while allowing for endogeneity of MV adoption itself. In the India study, this was accomplished as follows.

1. The profitability of MVs for rice was measured by state ratios of MV rice yields to yields of traditional (unirrigated) rice.
2. Data were collected for “leading” rice varieties in India from 1978 to 1992. In selected districts, yield traits for the three leading rice varieties were collected from farmers. The set of such varieties for each major agroclimatic region then

constituted a collection of ultimately successful varieties. For this set, it was possible through genealogical analysis and breeders' ratings to compute area traits in the set of varieties and to date them according to the date of release of the ultimately successful varieties. It was argued that these availability data were exogenous to farmers in that they represent breeders' success.

A complete supply-factor demand system based on profit maximization in MV adoption decisions, decisions on planted area, and yield (supply) outcomes was estimated. From these estimates, we can compute the implicit shadow prices for the trait values as impacts on farm revenue.

The estimates showed that price and revenue terms affected the decision on planted area as expected. They also affected the MV adoption decision.

The estimates clearly showed that traits affected the adoption of modern rice varieties and that they drove MV expansion beyond the original first-generation levels. The study concluded that the addition of genetic traits from generation 1 to generation 3 probably expanded MV areas by roughly one-third, that is, from 40% to 60% of area by 1984. By 1997, this had increased to 75%.

Thus, we can approximate the value of third- and fourth-generation traits as an expansion of modern rice area of 15–20% times the yield effect of modern varieties. This indicates a yield increase of roughly 1 t $ha^{-1}$ (a 65% increase).

Modern varieties also increased input use per hectare by about 10%, so the net productivity increase was probably on the order of 50%. This estimate was roughly double the earlier Gollin–Evenson estimate based on yield effects only.

## The MV production study

Evenson and Gollin (1997) report an MV production function study for rice. The dependent variable in the study was the production of rice varieties that meet official release standards in the locations for which they were produced (see Table 1). Observations were for NARS from 1965 to 1990. Varietal releases were categorized by the route or pathway from origin to release. These routes were described earlier.

The key endogenous variables to be explained were the annual varietal releases by route. This set of varieties by route is jointly determined by the set of explanatory variables.

The explanatory variables include variables measuring the International Rice Germplasm Collection (IRGC), the international rice plant breeding (IRPB) program, INGER activities, national demand, and national plant breeding (NPB) activities. Of these, the most complicated was the measure of INGER activities—NING, the number of nurseries in a country. Because this was chosen by country, it cannot be treated as an exogenous or predetermined variable. It was modeled as simultaneously determined along with the other endogenous variables.

The variables measuring IRGC and IRPB, on the other hand, can be considered to be predetermined and thus exogenous to the national-level variables. The IRGC, the cumulative number of catalogued IRGC accessions (with passport data), was considered to be a determinant of the number of INGER nurseries undertaken in a participating country. The IRPB activities were measured by the cumulative size of the internationally contributed landrace pool.

Other exogenous variables include the cumulated landraces, both international and national, which are measures of national plant breeding activity. In addition, the area planted to rice in a country should govern genetic resource flows because it reflects demand.

The two variables measuring the IRRI plant breeding program clearly indicated that it was the size of the IRRI-origin landrace pool that was important and not the cumulative stock. In other words, what seems to be important is the introduction of new landrace materials into the pool, not the replication of those landraces, which is largely the contribution of national programs. Each landrace added to the pool by IRRI contributed .045 varieties annually in each country as indicated by the statistically significant sum of the coefficients.

The coefficient estimates indicated that one additional INGER nursery is associated with 0.03 additional released varieties. Thus, the addition of 34 nurseries (a nursery was counted at each location in each year) adds one released variety. If the INGER program were to end (to be stopped at its level of 900 to 1,000 nurseries each year in recent years), the recent annual flow of released varieties would be reduced from 80 per year to around 60. Each landrace added from IRRI sources caused approximately 0.68 added varieties to be released in each future year.

The IRGC also has an impact on released varieties, because it induced the addition of INGER nurseries. Adding 1,000 accessions to the IRGC caused 5.8 added released varieties in each future year.

Evenson and David (1993) report estimates of the impacts of MVs for India, Pakistan, Bangladesh, Philippines, Thailand, Indonesia, and Brazil. These range from a relatively high value for India to lower values for the other countries. The approximate value of MVs in 1990 in indica rice regions was US$3.5 billion. Evenson and David consider this to be the cumulative contribution of the first 1,400 MVs, and obtain an average value of a released variety of US$2.5 million per year. This annual value continued into perpetuity because they are considering varietal improvements to be additive.

Using this estimate, Collin and Evenson computed the economic effects of INGER, of one added IRRI landrace, and of added accessions to the IRGC. They estimate that ending the INGER program would reduce the flow of released varieties by 20 per year. There is a time lag between a cultivar's appearance in INGER and production. Suppose this to be five years. Then further suppose that the INGER effect lasted only 10 years—in other words, that INGER speeded up the release of varieties that would have been released an average of 10 years later. The present value of the 20 varieties over the sixth and fifteenth year, discounted at 10%, is US$1.9 billion. At a 5% discount rate, the value rises to US$6 billion. This is clearly a large contribution relative to the costs of operating the system, and much of this value is due to genetic resources collections.

The present value of a landrace added to varieties by IRRI was US$86 million, discounted at 10% (US$272 discounted at 5%). For landraces added by NARS, this value was US$33 million (US$104 discounted at 5%).

Collin and Evenson also computed the present value of adding 1,000 catalogued accessions to the IRGC. Using the estimated coefficient for the impact on INGER nurseries (which was quite small), they computed the value of adding 0.52 nurseries to be roughly US$100 million, discounted at 10% (US$350 million discounted at 5%), assuming a 10-year lag between the incorporation of accessions into varieties and economic impact.

## Traditional studies of returns to rice research: evidence for varietal contributions

This section reviews 15 studies that might be considered traditional "returns to research" studies. Seven of the studies used varietal variables, usually measured as the percentage of area planted to modern varieties. The studies used a productivity decomposition framework, either treating rice yields as a productivity index or modeling an area-yield system (see below for a version of this framework). Three studies (India, Thailand, and the Philippines) used a duality-based system of rice supply and factor demand. A study for Indonesia used a rice total factor productivity measure.

Variables used in these studies to measure determinants of productivity (at the district or regional level—all studies used secondary data) included:

- **Rice research,** measured as a "stock" designed to be proportional to the flow of productivity improvements in farmers' fields. This stock took into account both timing and spatial spill in dimensions.
- **High-yielding varieties,** measured as the percentage of rice area planted to modern or high-yielding varieties of rice. This variable was usually treated as endogenous at the farm level but exogenous at the district level (see the next part of this paper for an endogenous treatment of the HYV variable).
- **Extension supply,** usually measured as the ratio of extension staff to the farm population potentially to be served.
- **Infrastructure** and related variables such as roads and market variables.

Table 4 summarizes results of the 15 traditional studies surveyed. All reported statistically significant coefficient estimates except for the TFP (upland rice) research estimates for Indonesia in 1995. The estimates of marginal value products are calculated as the estimated benefits per marginal dollar invested at the peak period from a timing perspective (i.e., spending in time $t$ is estimated to generate benefits in periods $t + l$, $t + 2$, etc., rising to a maximum in $t + n$ ). The marginal product is the benefits in period $t + n$. The estimated marginal internal rate of return is the interest or discount rate of this flow of benefits that sets its present value equal to one (i.e., to costs in time $t$).

As can be seen from Table 4, most estimated marginal products are high, as are the estimated marginal internal rates of return. For comparison, results of studies of

**Table 4. Rice research impact studies: a summary.**

| Study | Estimated coefficients | | | Estimated marginal products | | | Contribution | | Estimated marginal IRR[b] | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Research | HYV[a] | Extension | Research | HYV | Extension | Non-HYV | HYV | Research | Extension |
| India (McKinsey and Evenson 1991) | | | | | | | | | | |
| Yields | .034 | .549 | .083 | 11.3 | | 16.5 | .04 | .26 | 155 | 215 |
| India (Evenson 1994) | | | | | | | | | | |
| Yields | .178 | .257 | .035 | 20.0 | (.278) | 4.9 | .18 | .14 | 80 | 82 |
| Area | .115 | .241 | | | | | | | | |
| Indonesia (Salmon 1991) | | | | | | | | | | |
| Yields | .014 | | .050 | nc[d] | | nc | | | 151 | nc |
| Indonesia (Evenson 1995) | | | | | | | | | | |
| TFP[c] (IRR) | .140 | .015 | .011 | 0.9 | | 1.0 | .14 | .01 | 337 | 0 |
| TFP(upland) | neg | | .109 | neg | | 10.9 | | | 0 | 173 |
| Indonesia (Evenson et al 1994) | | | | | | | | | | |
| Yields (irrigated) | .003 | | 1.307 | 101 | | | | | 100+ | |
| Area (irrigated) | .696 | | | | | | | | | |
| Yields (upland) | .002 | | 2.090 | 20 | | | | | 100+ | |
| Area (upland) | .526 | | | | | | | | | |
| Pakistan (Azam et al 1991) | | | | | | | | | | |
| Yields (irrigated) | .016 | .109 | | 22.4 | (.109) | | .02 | .06 | 84 | |
| Bangladesh (Dey and Evenson 1994) | | | | | | | | | | |
| Yields (irrigated) | .048 | | .020 | 36.4 | | 2.9 | | | 165 | 45 |
| Philippines (Sardido and Evenson 1986) | | | | | | | | | | |
| Yields (irrigated) | 2.130 | | .016 | 30 | | 3.0 | | | 90 | 50 |
| Thailand (Setboonsarng and Evenson 1991) | | | | | | | | | | |
| Yields (irrigated) | .050 | .068 | .050 | 1.8 | | 1.0 | .05 | .04 | 35 | 15 |
| Brazil (Avila and Evenson 1996) | | | | | | | | | | |
| Yields | .020 | | .059 | 1.6 | | 4.9 | | | 43 | 86 |
| 10 Asian countries (Evenson 1991) | .075 | | .192 | | | | | | 59 | 780 |

[a] HYV = high-yielding varieties. [b] IRR = internal rate of return. [c] TFP = total factor productivity. [d] nc = not calculated.

research on other commodities are also included in Table 4. Of all of these commodity studies, rice research studies report the highest estimated marginal internal rates of return.

The coefficients reported in the studies where a varietal variable was included as a determinant are at least suggestive of the relative importance of varietal improvement. Suppose that over the 15 years from 1970 to 1985 the HYV percentage increased from 10 to 60. This would have produced a productivity increase of $50 \times C_{HYV}$, where $C_{HYV}$ is the HYV coefficient. Over the same period, the contribution of research unrelated to varietal improvement would have been $R^* \times C_{RES}$, where $R^*$ is the percentage increase in the research variable over the 15 years as a result of nonvarietal rice research. If nonvarietal research is roughly half of total rice research, $R^*$ would be roughly 100% (i.e., a doubling). Using these calculations, we would attribute from one-third to two-thirds of the productivity growth induced by rice research to varietal improvement.

## Prospects for future genetic improvements

Projections of future genetic improvements in crops are typically based on a considerable amount of experimental evidence, but little field evidence (except for hybridization). The new plant type developed at IRRI shows promise (Khush 1996), but its full impact on productivity has yet to be realized. Hybrid indica rice materials have now reached the commercialization stage. In India, they show some success to date, but their full potential has yet to be shown. Wide crossing techniques have been used to introduce genes of wild species into *Oryza sativa,* and *O. nivara* is a widely used source of host-plant resistance to grassy stunt virus. Again, the full potential of these techniques has not been realized. Transgenic indica rice plants have been available for several years, but are only now reaching the testing stage.

Rosegrant and Evenson (1996) have made a rice yield projection based on a recent priority-setting study carried out as part of a Rockefeller Foundation study conducted with IRRI and the Economic Growth Center at Yale University. A rating exercise was done with 18 senior rice scientists (nine from IRRI, nine from NARS). For each set of research problem areas and research techniques, four ratings were elicited for alternative research techniques: managerial research, conventional breeding, wide crossing and hybridization, and biotechnology (transgenic rice and marker-aided selection). Ratings were on a scale of 1–5 and were calibrated to percentage achievements of economic potential: (1) a rating of achievement to date, (2) a rating of potential achievement, (3) an estimate of the number of years required to achieve 25% of the difference between achievement to date and potential (Y25), and (4) an estimate of the number of years required to achieve 75% of the difference between achievement to date and potential (Y75). In developing their estimates, scientists were asked to assume that in future periods both international and national research programs would continue to be supported at the levels of the past decade.

**Table 5. The South Asia rice nonprice (yield) base projections (expressed in percentage).**

| | 1995–2000 | 2000–2005 | 2005–2010 | 2010–2015 | 2015–2020 |
|---|---|---|---|---|---|
| Public research | | | | | |
| Management | .22 | .22 | .22 | .22 | .22 |
| Conventional breeding | .76 | .65 | .44 | .33 | .22 |
| Wide crossing, hybrids | .10 | .20 | .30 | .25 | .15 |
| Biotechnology | .16 | .32 | .47 | .68 | .79 |
| Total public research | 1.24 | 1.39 | 1.43 | 1.48 | 1.37 |
| Extension—schooling | .47 | .57 | .60 | .59 | .57 |
| Private research | .10 | .15 | .20 | .20 | .20 |
| Markets—infrastructure | .15 | .15 | .20 | .20 | .20 |
| Total base case | 1.96 | 2.26 | 2.42 | 2.47 | 2.34 |

The specification of two ratings, one for achievement to date and one for potential achievement, forced respondents to focus on "remaining potential." Ratings of potential minus achievements to date were summarized and converted to percentage accomplishments (note that scientists were given the ratings—the percentage achievement relationship—but were asked to rate using the 1–5 scale).

Rosegrant and Evenson developed projections of the public rice research contribution by period using the timing estimates of the 2.5% achievement and the 75% achievement levels to "distribute" economic gain achievement by subperiod. Scientists' estimates indicated that management (agronomy and related research) gains would be realized at a roughly constant rate over time. Conventional breeding gains were projected to decline as Mendelian combinations of genetic resources within the species were exhausted. The wide crossing/tissue culture technologies were expected to reach their maximum contribution around 2010. The contribution of biotechnology (transgenic plants and marker-aided selection) grows over time, with the major contribution coming after 2010.

Rosegrant and Evenson then applied crop-loss and potential yield data to develop projections for rice productivity gains. These are summarized for South Asia in Table 5. (Other projections for Southeast Asia and other regions are reported in Rosegrant and Evenson 1996.) The public research component is based on the probability-based (and crop-loss-based) estimates. These estimates indicate that the expansion of gains from wide crossing, hybridization, and transgenic breeding will offset conventional breeding exhaustion but that gains will not return to the level seen during the Green Revolution of 1962–82.

Other sources of productivity growth include extension, schooling, research in the private sector, and markets and infrastructure. These are based on productivity studies in several countries.

This exercise is based on judgments, but they are informed judgments by the rice scientists best qualified to make them. They show that varietal improvement is likely to continue to be the centerpiece of rice productivity gains.

## References


Avila AF, Evenson RE. 1996. Productivity change and technology transfer in the Brazilian grain sector. Rev. Econ. Rural.

Azarn QT, Bloom EA, Evenson RE. 1991. Agricultural research productivity in Pakistan. Islamabad (Pakistan): Agricultural Research Council.

Dey MM. Evenson RE. 1991. The economic impact of rice research in Bangladesh. Gazipur (Bangladesh): Rice Research Institute, and Manila (Philippines): International Rice Research Institute, and Dhaka (Bangladesh): Bangladesh Agricultural Research Council.

Dwidjono H Darwanto. 1993. Rice varietal improvements and productivity growth in Indonesia. Ph.D. dissertation. University of the Philippines, Los Baños.

Evenson RE. 1991. IARCs, AID, and investment in national research and extension programs. In: Evenson RE, Pray CE. Research and productivity in Asian agriculture. Ithaca, N.Y. (USA): Cornell University Press.

Evenson RE. 1994. Analyzing the transfer of agricultural technology. In: Anderson JR, editor. Agricultural technology: policy issues for the international community. Wallingford (UK): CAB International.

Evenson RE. 1998a. Crop-loss data and trait value estimates for rice in Indonesia. In: Evenson RE. Gollin D, Santienello V, editors. Agricultural values of plant genetic resources. Wallingford (UK): CAB International. Chapter 12.

Evenson RE. 1998b. Modern varieties, traits, commodity supply and factor demand in Indian agriculture. In: Evenson RE, Gollin D, Santienello V, editors. Agricultural values of plant genetic resources. Wallingford (UK): CAB International. Chapter 11.

Evenson RE. 1998c. Rice varietal improvements and international exchange of rice germplasm. In: Pingali P, Hossain M, editors. Impact of rice research. Proceedings of the International Conference on the Impact of Rice Research, 3-5 June 1996, Bangkok, Thailand. Thailand Development Research Institute, Bangkok. Thailand, and International Rice Research Institute, Manila, Philippines. p 51-82.

Evenson RE, Abdurachman E, Hutabarat B, Tubagus AC. 1994. Economic impacts of agricultural research in Indonesia. Bogor (Indonesia): Winrock International, and New Haven, Conn. (USA): Economic Growth Center, Yale University.

Evenson RE, David C. 1993. Adjustment and technology: the case of rice. Paris (France): Organization for Economic Cooperation and Development.

Evenson RE, Pray C, Rosegrant M. 1996. Sources of agricultural productivity growth in India. Research Report of the International Food Policy Institute. Unpublished.

Gollin D, Evenson RE. 1998. An application of hedonic pricing methods to value rice genetic resources in India. In: Evenson RE, Collin D, Santienello V, editors. Agricultural values of plant genetic resources. Wallingford (UK): CAB International. Chapter 9.

Collin D, Evenson RE. 1993. Genetic resources and rice varietal improvement in India. Economic Growth Center, Yale University, New Haven, Conn., USA.

Evenson RE, Collin D. 1997. Genetic resources, international organizations, and improvement in rice varieties. Econ. Dev. Cult. Change 45(3):471-500.

Khush GS. 1996. Prospects of and approaches to increasing the genetic yield potential of rice. In: Evenson RE, Herdt RW, Hossain M, editors. Rice research in Asia: progress and priorities. Wallingford (UK): CAB International. p 59-72.

McKinsey J, Evenson RE. 1991. Research, extension, infrastructure and productivity change in Indian agriculture. In: Evenson RE, Pray CE, editors. Research and productivity in Asian agriculture. Ithaca, N.Y. (USA): Cornell University Press.

Rao KDC, Evenson RE. 1998. Varietal trait values for rice in India. In: Evenson RE, Gollin D, Santienello V, editors. Agricultural values of plant genetic resources. Wallingford (UK): CAB International. Chapter 10.

Rosegrant MW, Evenson RE. 1996. Productivity projections for commodity market modeling. Economic Growth Center, Yale University, New Haven, Conn., USA.

Salmon DC. 1991. Rice productivity and returns to rice research in Indonesia. In: Evenson RE, Pray CE, editors. Research and productivity in Asian agriculture. Ithaca, N.Y. (USA): Cornell University Press.

Sardido ML, Evenson RE. 1986. Regional total factor productivity change in Philippine agriculture. J. Philip. Devel. 13.

Setboonsarng S, Evenson RE. 1991. Technology, infrastructure, output supply and factor demand in Thailand's agriculture. In: Evenson RE, Pray CE, editors. Research and productivity in Asian agriculture. Ithaca, N.Y. (USA): Cornell University Press.

## Notes

*Author's address:* Economic Growth Center, Yale University, New Haven, Connecticut, USA. robert.evenson@yale.edu

*Citation:* Dowling NG, Greenfield SM, Fischer KS, editors. 1998. Sustainability of rice in the global food system. Davis, Calif. (USA): Pacific Basin Study Center, and Manila (Philippines): International Rice Research Institute.

CHAPTER 19

# Food, energy, and the environment: implications for Asia's rice agriculture

V. Smil

Rice is now the world's largest cereal crop, but its share of typical Asian diets has been decreasing because the grain is being displaced by greater consumption of wheat and animal foodstuffs. Nevertheless, total harvests will have to increase to satisfy Asia's growing population. Because of continuing losses of rice fields to urbanization and industrialization—the process that also leads to the loss of valuable ecosystem services—this will have to be done largely through higher yields. Two inevitable consequences of the necessary increased use of fertilizer will be higher inputs of reactive nitrogen into the environment and an increased generation of greenhouse gases.

Rice—to use a classic mental model from a country that produces more of the grain than any other nation in the world—is a perfect yin-yang crop. Recently, after being a perennially close number two, it surpassed wheat to become the world's largest cereal cropand yet the grain's consumption is on a clear long-term decline. A peculiar agroecosystem created by its cultivation is, on balance, a definite environmental asset—but in too many places in Asia it is treated just like any other piece of readily disposable real estate, to be converted to low-rise factories turning out more shoddy goods for Wal-Marts of the world. Consequently, the crop's future looks both assured—and uncertain.

I will look at these contradictory realities as I examine three critical factors that will determine the long-term fortunes of Asian rice production: first, the grain's role as a major staple, then a few basic conditions needed for a continuing growth in output, and finally some major environmental benefits, and impacts, of rice agriculture.

Because the time perspective of my musings is at least one human generation—20 to 30 years depending on the fertility pattern—I will look at matters that are not usually considered when thinking about the near—term future of rice agriculture, matters ranging from the misunderstood lactose intolerance in East Asia to the rising crude oil imports in the United States. Long-term effects of such indirect connections are obviously hard to quantify, but their potential impacts may be quite substantial.

## A (not so) unique food

Rice has its obvious share of unique attributes when compared with other major staple grains—yet the grain is also very much like any other food cereal as its intake changes with advancing dietary transitions. For all food cereals—be it wheat, millet, rice, or rye—this has meant only one thing in the long run: declining average per capita consumption. As average per capita incomes have risen, staple grain consumption (as well as the eating of legumes and tubers) has gone through three virtually universal phases.

Where the premodernization intakes of staples were barely adequate, increased income first brings a slight to substantial rise in average per capita consumption (only the highest income classes usually do not participate in this shift). This increase culminates in a brief plateau, and is followed by a sometimes gradual, but often surprisingly rapid, decline (FAO 1996).

This transition can be very fast: China's experience has encompassed this whole spectrum in less than a single generation. The country's average annual per capita rice consumption first rose, from less than 140 kg of unmilled grain in 1975 to a peak of 170 kg in 1984, but since that time it fell to about 150 kg (State Statistical Bureau 1995, Crook 1996). And a careful observer of today's Chinese eating habits in every richer part of the country knows that a great deal of rice reaching tables actually ends as pig feed—so the real intake rate is almost certainly even lower.

India and Vietnam are clearly in the first category of dietary transition, as both countries still do not enjoy the benefit of a comfortable food supply (that is, their average daily per capita food energy and protein availability are not at least 20–25% above the metabolic requirement compatible with healthy and vigorous lives).

In contrast, average rice intakes have declined with particular rapidity in the newly industrialized countries of East Asia. During the past generation, Japan's average rice consumption has decreased by more than 25% to 75 kg of milled grain in 1995 (Statistics Bureau 1995). During the same time, consumption in South Korea fell by more than a third (to 120 kg in 1995) as did the Taiwanese intake. Moreover, this trend appears to be continuing.

There are three distinct reasons for the decline in rice consumption. The first two are shared with other staple cereals. Less strenuous physical work in increasingly urbanized societies requires lower average daily per capita food intake, and higher incomes push the eating pattern up the food chain, resulting in higher consumption of animal foods, fats, sugar, and alcohol.

The third reason is peculiar to rice, whose consumption is being displaced by higher direct, and indirect, intakes of wheat, maize, and soybeans. The first crop competes directly with rice as a more flexible foodstuff convertible to noodles, bread, and a multitude of leavened, or unleavened, baked products. Diffusion of bread, even in societies where this highly convenient foodstuff was traditionally absent, is closely tied to urbanization, and this assures that all populous Asian nations will demand much more wheat during the coming generation.

The other two crops lower rice consumption by providing efficient feed for more production of meat and dairy products. Although most people are aware of the inroads being made by bread, wheat noodles, and meat during the dietary transition in Asia, I have found that relatively few appreciate the enormous potential of dairy products for changing a country's dietary pattern.

Contrary to general perception, Asia's common biochemical peculiarity—a widespread intolerance of lactose (or lactase deficiency) among adults—does not prevent most people from drinking smaller, but nutritionally significant, volumes of whole milk. In addition, this intolerance is largely irrelevant for eating fermented dairy products—yoghurt has less lactose than raw milk, and ripe, hard cheeses contain mere traces of the milk sugar.

Japanese experience is an excellent proof that neither the widespread lactose intolerance nor the traditional absence of milk in a nation's food culture are obstacles to healthy dairy intakes. Japan's per capita mean consumption of dairy foods is now well over 50 kg a year, from zero in 1945. Because China's mean intake of dairy products is a mere 2 kg, it is easy to appreciate the potential for major gains during the coming generation.

But because of the enormous environmental and socioeconomic differences among Asian countries, it would be naive to claim that the East Asian pattern in general, and the Japanese path in particular, will be followed with predictable regularity elsewhere on the continent. Consequently, only a qualitative conclusion is safe: more rice will be produced not because most of the people who eat it want to consume more of it—but simply because there will be more people in countries where the grain has been a traditional staple.

Absolute production has increased steadily, and, barring a magical slowdown in population growth, this trend is bound to continue for at least another generation. In contrast, uncertainties about the rates of population increase and the extent and the rapidity of dietary transitions make any quantitative estimates questionable.

Inevitably, longer forecast periods open wider ranges of population projections, but different assumptions, particularly about average fertility rates, may cause totals to be hundreds of millions of people apart. According to the medium variant of the United Nations population projections, Asia would have about 4.8 billion people in the year 2025, with a low of 4.4 billion and a high of 5.1 billion (United Nations 1998).

Even the medium forecast represents more than a 40% gain (the 1995 total was about 3.4 billion). Merely to maintain existing per capita rice intakes would call for a commensurate increase in Asian harvests—but a fast dietary transition could cut the total by as much as 20–30%, or to less than a third above the 1995 harvest. In contrast, faster population growth and slower rates of economic development could call for up to a 60% increase. Consequently, plausible supplies that would have to be met even during a period of a single generation can differ roughly by a factor of two!

## Two essentials for continued growth

Whatever the eventual rate of increase, rice production will be expanding for at least the next generation, and most likely also for one after that. The three most fundamental biophysical imperatives that would allow this expansion are adequate availabilities of farmland, water, and nutrients. Although continent-wide generalizations are always subject to numerous exceptions and caveats, especially when projected over a period of 20–25 years, I would argue that the availability of water will be a relatively minor constraint to overall production; that while it will be possible to supply all needed nutrients, the cost may be much higher than generally imagined; and that losses of farmland will begin to raise some serious questions about long-term nutritional security.

## Nutrients for expanded production

The nutrient challenge is above all the matter of delivering enough nitrogen. Although rice has a lower protein content than maize, and it contains only about half as much of it as the most proteinaceous wheat, the crop's rising yields translate into high nitrogen demands, both in relative terms and in the absolute global demand.

The global rice crop of the mid-1990s incorporates every year about 13 million t of nitrogen—about 70% of it in grain, the rest in straw and roots—or roughly 90 kg N $ha^{-1}$. Actual application rates range from less than 50 to well over 400 kg N $ha^{-1}$. Dependence on N fertilizers cannot be calculated precisely, but a good estimate is not difficult to make. Assuming that annual nitrogen mineralization averages no more than 15 kg N $ha^{-1}$, that atmospheric deposition supplies around 10 kg N $ha^{-1}$, and that biofixation (the combination of nitrogen fixed by cyanobacteria, by *Azolla-Anabaena* symbiosis, and by leguminous crops preceding rice) adds as much as 20 kg N $ha^{-1}$, the natural processes would provide about 45 kg N $ha^{-1}$. With an average assimilation rate of less than half of all available nitrogen, this would supply at best a quarter of the needed nutrient.

Consequently, about three-quarters, and certainly no less than two-thirds, of all nitrogen needed by today's global rice crop must come from fertilizers, which means overwhelmingly from urea. With typical fertilizer use efficiencies of between 40% and 50%, this would mean that the global rice crop claims around 20 million t of N in synthetic fertilizers, or about a quarter of the worldwide production. This share will almost certainly rise in the future, and the average fertilizer price will be a critical variable in the production of larger crops.

In 1975, the international price of 1 t of urea (expressed in constant 1990 dollars) was about US$440, that is, nearly US$940 $t^{-1}$ of N. In 1995, it was only about US$(1990)180, just 40% of the level a generation ago—and at first sight there seems to be no reason why this combination of plentiful supply and low prices should not continue.

Today's global oil market is clearly very user-friendly: when adjusted for inflation, the price of crude oil (at about US$15 $barrel^{-1}$ of Arabian light) is as low as it was before 1973, when the Shah of Iran and the Saudi royal family decided to quintuple the price, which in 1980 more than tripled again with the coming of the Ayatollah Khomeini. Moreover, there has never been so much oil around: global crude oil reserves are at a historic high, with the reserve-production ratio at close to 50 years.

Two other variables are also at their historic highs—and rising. The first one is the Organization of Petroleum Exporting Countries' (OPEC) share of oil riches. The oligopoly may be enfeebled but it still controls almost 80% of all known crude oil, two-thirds of it in just five Persian Gulf countries—Saudi Arabia (a quarter) and four of its neighbors.

The second variable is the level of steadily rising global imports. In particular, U.S. crude oil imports are at their historic high, surpassing half of the country's consumption, and China has just turned from a substantial crude oil exporter to a rapidly rising importer. Latent oil demand in other large Asian nations, above all in India, cannot be satisfied by their domestic resources.

These realities may matter little in the short term, but 10–20 years from now things may be very different. Even a fairly conservative energy consumption outlook sees the overall demand rising by 50% compared with the 1995 level by the year 2015 (Energy Information Administration 1996). And even if the Gulf's wobbly monarchies and dictatorships do not fall and destabilize the oil price, the region remains the only assured long-term source of crude oil. As non-OPEC oil resources, developed aggressively after 1973, decline, OPEC's power as the supplier of last resort will reassert itself. Although I do not forecast any particular timing or price level, I believe that an eventual third round of oil price rises is inevitable.

Because crude oil and natural gas are interchangeable in many markets, rising prices of the first commodity would, as before, inevitably push up the prices of the second one. As the Haber-Bosch ammonia synthesis is now overwhelmingly dependent on natural gas, both as the feedstock (source of H) and to energize the synthesis, these price shifts would inevitably be reflected by the fertilizer market.

Moreover, unlike in the early 1970s when many ammonia-urea plants were relatively inefficient, only limited energy savings could be realized by adjusting the bulk of today's installed capacity. In the early 1970s, it was common to consume more than 100 GJ $t^{-1}$ of nitrogen shipped as urea; today's plants commonly produce the nutrient with less than 70 GJ $t^{-1}$. Depending on the combination of future hydrocarbon prices and energy use efficiencies, we may see only a gradual rise in nitrogen fertilizer prices—but levels three times as high, in constant monies, as today are quite possible within a generation.

Of course, by 2025 this fact may be only a minor complication for transgenic crops able to secure nearly half of their nitrogen supply, but I would counsel a great deal of caution when assessing the prospects for a routine transfer of symbiotic nitrogen fixation to nonleguminous crops. A generation ago, we were assured that by now the practice would be common!

## Loss of rice fields

Even with unprecedented efforts to control the loss of farmland to urban, industrial, and infrastructural construction, declines in periurban and coastal rice lands will continue in every populous Asian country. Asian-wide summation of these losses is impossible because of highly unreliable data on annual farmland losses and because of substantial interannual fluctuations. China's example, certainly the most important one, will illustrate the magnitude of these losses.

Since the beginning of the Deng Xiaoping-inspired modernization drive in 1979, China's annual farmland loss has fluctuated from a low of 200,000 ha to as much as one million ha, and the mean for the period has been about 500,000 ha (Smil 1993). Rice fields account for at least one-fifth of these losses, that is, about 100,000 ha a year. Even if the multicropping ratio of this lost land were no higher than the national mean of about 1.5, this loss would represent an annual decline of 150,000 ha of sown rice.

With average yields of 6 t $ha^{-1}$ in 1995, harvests of some 900,000 t of rice from 150,000 ha of rice fields represent (at roughly US\$350 $t^{-1}$) an economic loss of some US\$300 million a year, a decidedly minor sum when compared with China's current foreign earnings (the country's trade surplus with the United States is now well above US\$40 billion). But such a simple monetization offers a misleadingly reassuring perspective. Implications of the continuing land loss for food security and its environmental toll are substantially higher.

Nutritional dimension of this loss is best illustrated by translating it into annual food production equivalents—or comparing it with some foreign farmland and production totals. A harvest of 900,000 t of rice could supply annual consumption (averaging about 150 kg of unmilled rice per person in 1995) of some six million Chinese, or roughly half of the country's annual population increase.

A cumulative loss of at least one million ha of rice fields since 1979 is an equivalent of losing food production capacity to feed at least 40 million people, an equivalent of Spain or two Malaysias. Even if stricter Chinese controls could keep the annual rate of rice field losses to just 50,000 ha—a most unlikely assumption given the continuing frenzy of large-scale construction, the mushrooming of small- and medium-scale rural enterprises, and the emerging suburbanization—the country would lose another 1.25 million ha during the next generation, a loss larger than South Korea's rice land in cultivation today. Considering the fast pace of China's economic development, rice field losses two or three times as large are easy to imagine.

Facing such large losses of farmland, China does not have the option Japan, South Korea, and Taiwan had, that is, to turn to massive grain imports. To import just 15% of its current rice consumption, China would need more than the total amount of the grain traded worldwide! And it would not be easier if the country tried to import more wheat or maize: covering just one-quarter of its current need by imports (still far below the shares now brought in by South Korea, Taiwan, and Japan) would make China the world's largest buyer of grain, appropriating about half of the world's total supply!

Given these realities, countries with relatively rapidly declining rice lands should at least make sure that such land is not simply abandoned. Yet this abandonment is now a widespread occurrence, demonstrable even in places where per capita availability of arable land is lower than in China. Preston (1989) found these phenomena even in central Java, the world's most densely inhabited rural region.

## Environmental benefits and effects of rice cultivation

Such an extensive agroecosystem as rice fields—they now account for about one-tenth of the world's cultivated land—would have appreciable environmental effects even if it would not be so different from dry crop farming. The peculiarity of this agroecosystem makes it indisputably an even more valuable asset than dry fields, and steps toward a proper valuation of these undoubted environmental benefits would be extremely helpful in arresting the disappearance of rice fields.

Of course, like any other intensive agroecosystem, rice cultivation has its negative effects on the environment. The two concerns that may become more prominent in the long run are the excessive presence of reactive nitrogen in water, and the generation of greenhouse gases.

### Valuing rice fields

By the late 1980s, it became clear that we will have to develop a new economics consonant with the long-term maintenance of biospheric integrity. Meeting this challenge will require many actions, but better ways of valuing environmental goods and services cannot be absent from any sensible list of desirable goals. Without a more realistic valuation of natural inputs, we will not be able to first moderate the rates, and eventually reverse the process, of worldwide environmental degradation.

I am well aware of many arguments against this approach, and I recognize that what we can do today is still very fragmentary, and that in many instances of environmental valuation there may be no generally acceptable solutions even in the more distant future. But I would argue that the sustainability of agroecosystems and the promotion of desirable farming practices will remain elusive goals in the absence of proper valuations that take into account unique and perpetual ecosystemic services and that express, albeit imperfectly, their inherently high evolutionary and energetic worth.

A critical example illustrates the necessity and the challenge of this approach. Although the ecosystemic value of continued land losses is difficult to evaluate, it is undoubtedly a multiple of the foregone profit. A study prepared by the Mitsubishi Research Institute for the Japanese Ministry of Agriculture, Forestry and Fisheries estimated that what it called "the land and environmental preservation function of rice paddies" is worth ¥(1990)12 trillion a year, or three times the total value of Japanese rice production (Yoichi 1992).

This estimate encompassed the following environmental benefits of wet fields: they have a long-term beneficial effect on soil quality; they prevent the leaching of nitrogen and hence, given the high rates of fertilization in all intensive rice agricultures, a widespread pollution of groundwater and surface water by nitrates; they reduce the risk of floods; they provide a habitat for a number of otherwise beneficial species; and, undoubtedly, they generally beautify a landscape.

This is hardly an exhaustive list. I would add to it above all the irreplaceable ecosystemic services rendered by bacteria thriving in wet fields. Asian rice fields would lose a large share of their productivity without the ubiquitous presence of both free-living and symbiotic nitrogen-fixing bacteria supplying an essential macronutrient for the staple crop. Annual rates of this biofixation can be impressively high (Giller and Wilson 1991), but considering just the value of the fixed nitrogen in terms of its equivalent in a commercial fertilizer would be yet another form of undercounting as the diazotrophs also supply organic matter to maintain soil structure and organic carbon needed to feed microorganisms, invertebrates, and fish living in paddy waters.

Even such a limited ecosystemic valuation of rice fields (leaving aside any considerations of biodiversity) would improve probabilities of their protection. At the same time, a truly long-term sustainability of rice cultivation will require better management of undesirable environmental effects of intensive wet-field cultivation: nitrates in water and the generation of greenhouse gases are the two concerns with extended impact horizons.

## Reactive nitrogen from fertilizers

The presence of excessive amounts of reactive nitrogen in groundwater, streams, lakes, and ponds has become a ubiquitous problem in all European countries, and a concern in parts of North America's intensively cultivated regions, above all in the Corn Belt and in California (Smil 1997). This has led to limits on how much fertilizer can legally be applied. In 1991, the European Union issued a nitrate directive that aims at limiting combined applications of synthetic fertilizers and organic wastes to no more than 170 kg N $ha^{-1}$, compared with today's applications, which commonly more than double that rate.

Similar limits would be crippling for many intensively cultivated rice-growing regions in Asia, where annual applications exceed 300 kg N $ha^{-1}$. Yet in spite of these high, and still-rising, applications, Asian waters have so far shown only a limited evidence of nitrogen enrichment. Although nitrate concentrations in most major rivers have gone up, ponds and wells do not appear to contain nitrate levels comparable to those common in Western Europe—or in Iowa (USA).

What seems to have made the most difference is the environment conducive to denitrification, to the return of dissolved nitrate back to atmospheric $N_2$, carried out by a large number of aerobic bacteria (*Pseudomonas, Bacillus,* and *Alcaligenes* are the most common heterotrophic genera). Bacterial denitrification in soils is promoted by high nitrate and low oxygen concentrations, higher moisture content, fairly high temperatures (optima around 25 °C), near-neutral pH, and plenty of decomposable organic matter available for the heterotrophic denitrifiers. All of these conditions are commonly present in Asian rice fields.

But this does not mean that Asian waters are immune to the problem of excessive reactive nitrogen. With rising rates of fertilization, the situation will get worse. Both the United States and European experiences illustrate this risk. The Mississippi River, whose watershed receives about 40% of all fertilizer applied in the U.S., had fairly low and constant nitrate levels between 1905 (when the monitoring started) and the early 1970s, but since then typical nitrate concentrations have increased more than fourfold.

The Dutch have used more fertilizer nitrogen than any other country for decades, and nitrate concentrations in their drinking water started to rise sharply during the early 1970s. A decade later, they surpassed the maximum recommended by the European Union—which, at 25 mg $NO_3$ $L^{-1}$ is 2.5 times higher than the U.S. standard—and by the mid-l980s, they were above 40 mg $NO_3$ $L^{-1}$.

Because of the high levels of both inorganic and organic nitrogen applications, it is inevitable that elevated nitrate levels must already exist in many intensively fertilized locales, and a larger-scale takeoff of groundwater loadings can be expected during the next decade or soon afterwards. Health effects of high nitrate loadings are potentially life-threatening methemoglobinemia among infants and higher risks of stomach cancer among adults. High nitrate loadings also contribute to eutrophication, the excessive algal blooms whose subsequent decay deprives affected waters of most of their oxygen supply and kills fish and other vertebrates.

## Greenhouse gases from rice fields

Much like any intensive farming that relies on high applications of synthetic nitrogen fertilizers, rice cultivation is a growing producer of nitrous oxide ($N_2O$) resulting from bacterial denitrification. In addition, unlike dry farming, rice agriculture is a relatively large source of methane ($CH_4$). These two greenhouse gases are much less abundant than $CO_2$ released from the combustion of fossil fuels and from land-use changes, above all from tropical deforestation (Smil 1997).

But because both gases are more effective absorbers than $CO_2$, their relative global warming potential is considerably higher. Over a relatively short period of 20 years, every $CH_4$ molecule is about 60 times, and every $N_2O$ molecule about 270 times, more effective as a greenhouse gas than $CO_2$. Over a period of 100 years, the two values change to, respectively, about 20 and 290.

Estimates for all anthropogenic sources of $CH_4$—anaerobic fermentation of organic matter in flooded soils and of solid wastes in landfills, enteric generation of the gas by ruminant livestock, emissions from coal mines, and losses during production, processing, and transportation of natural gas—range from less than 300 to nearly 600 million t $yr^{-1}$. Uncertainties about the anthropogenic flux of $N_2O$ are even greater. Fertilizer nitrogen is released as $N_2O$ through denitrification, and this bacterial conversion shows enormous differences in diurnal and seasonal rates. Consequently, global estimates of $N_2O$ from denitrification range from a mere 15,000 t to as much as 3.5 million t.

The atmospheric concentration of methane has more than doubled during the past 200 years, and $CH_4$ now accounts for about 15% of the anthropogenic radiative forcing. Emission rates of $CH_4$ are a complex function of several environmental variables—above all ambient temperature, soil chemical and physical properties, and the presence of root exudates—as well as agricultural practices (most notably water and crop residue management).

Not surprisingly, short-term measurements result in fluxes differing by several orders of magnitude, and global estimates of methane generation from rice fields have ranged from just 20 to 200 million t of $CH_4$ a year (Neue 1993, Wahlen 1993). Assuming that methane from rice fields has provided at least one-fifth of this share, about 3% of the global warming effect can be attributed to rice cultivation.

In contrast, $N_2O$ does not account for more than 6% of global radiative forcing. Even if two-thirds of $N_2O$ emissions were coming from nitrogen fertilizers, then rice cultivation would contribute about one-sixth of the global forcing attributable to the gas. Combined $CH_4$ and $N_2O$ forcing caused by rice cultivation would thus be equal to some 4% of the global greenhouse gas total, a marginal figure compared with $CO_2$ from the combustion of fossil fuels, a total that includes many obviously frivolous applications.

Nevertheless, should a clear signal of pronounced global warming in the early 21st century force some aggressive steps toward $CO_2$ reduction, rice's share of the global warming potential could increase. Today, it is too soon to tell whether this may become a factor in the crop's future fortunes.

## References


Crook FW. 1996. Good grain crop projected for 1996. In: China situation and outlook series. Washington, D.C. (USA): United States Department of Agriculture. p 21.

Energy Information Administration. 1996. International energy outlook 1996. Washington, D.C. (USA): EIA.

FAO. 1996. Food balance sheets. Electronic database. Rome (Italy): FAO.

Giller KE, Wilson KJ. 1991. Nitrogen fixation in tropical cropping systems. Wallingford (UK): CAB International.

Neue HU. 1993. Methane emissions from rice fields. Bioscience 43:466-473.

Preston DA. 1989. Too busy to farm: under-utilisation of farmland in Central Java. J. Dev. Stud. 26:43-57.

Smil V. 1993. China's environmental crisis. Armonk, N.Y. (USA): M.E. Sharpe.

Smil V. 1997. Cycles of life. New York, N.Y. (USA): Scientific American Library.

State Statistical Bureau. 1995. China statistical yearbook. Beijing (China): SSB.

Statistics Bureau. 1995. Japan statistical yearbook. Tokyo (Japan): Statistics Bureau.

United Nations. 1998. The world population projections: 1996 revision. New York, N.Y. (USA): United Nations.

Wahlen M. 1993. The global methane cycle. Annu. Rev. Earth Planet. Sci. 21:407-426.

Yoichi T. 1992. An environmental mandate for rice self-sufficiency. Jpn. Quart. 39:34-44.

## Notes

*Author's address:* University of Manitoba, Winnipeg, Canada. Vsmil@cc.umanitoba.ca

*Citation:* Dowling NG, Greenfield SM, Fischer KS, editors. 1998. Sustainability of rice in the global food system. Davis, Calif. (USA): Pacific Basin Study Center, and Manila (Philippines): International Rice Research Institute.

# Part VI:
# Case Studies

CHAPTER 20

# Rice production constraints in China*

Justin Yifu Lin

This paper reports the results of two surveys, one on agronomists at the agricultural bureaus in China's rice-producing prefectures and the other on scientists at China's various rice research institutions. In the study, two yield gaps are identified. Yield gap I refers to the difference between the highest experimental yield and potential farm yield under favorable conditions. This gap reflects the differences between the characteristics of experimental varieties and existing farm varieties and between the environment of the experimental plot and farm fields. Yield gap II refers to the difference between potential farm yield under favorable conditions and actual farm yield, taking the existing farm varieties as given. This gap reflects the constraints arising from weather, soil, pests, diseases, and so on. The study finds that the highest experimental yield is about 16 t $ha^{-1}$, which is about three times the average farm yield in 1990. More than 70% of the gap between the highest experimental yield and the average farm yield belongs to yield gap I. Both yield gaps I and II can be attributed to a small number of factors. For yield gap I, important variety-related factors are canopy architecture, photosynthetic rate, and growth duration, and important environment-related factors are duration of sunshine, accumulated heat units, and soil condition. For yield gap II, the main constraints arise from low soil fertility; cold, waterlogged, and acid soil; drought, submergence, heat, and cold at the seedling, vegetative, and anthesis periods; lodging; weeds; sheath blight; and stem borer. Most of the above constraints for yield gaps I and II cannot be easily overcome by conventional breeding methods. Therefore, they are the potential areas where biotechnological research may have the highest returns.

Rice is China's most important grain crop. Thirty percent of the country's grain area was planted to rice in 1991 (Fig. 1). Rice's output represented 42% of the total grain output in the same year (Fig. 2). Because of the importance of rice as a food grain in China, rice research holds a significant position in the nation's research on agriculture. (Previous studies show that research resource allocation in China was consistent with the pattern predicted by the Schmookler-Grilickes hypothesis of market-demand

---

*This paper draws heavily on Justin Yifu Lin and Minggao Shen. 1996. Rice production constraints in China. In: Evenson R et al, editors. *Rice research in Asia.* Wallingford (UK): CAB International. This research is supported by the Rockefeller Foundation's Grant RF 91004-1.

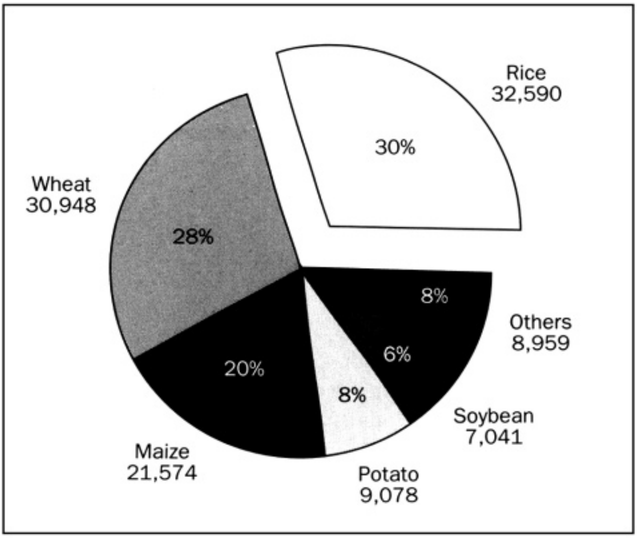



**Fig. 1.** Composition of grain area in thousands of hectares.

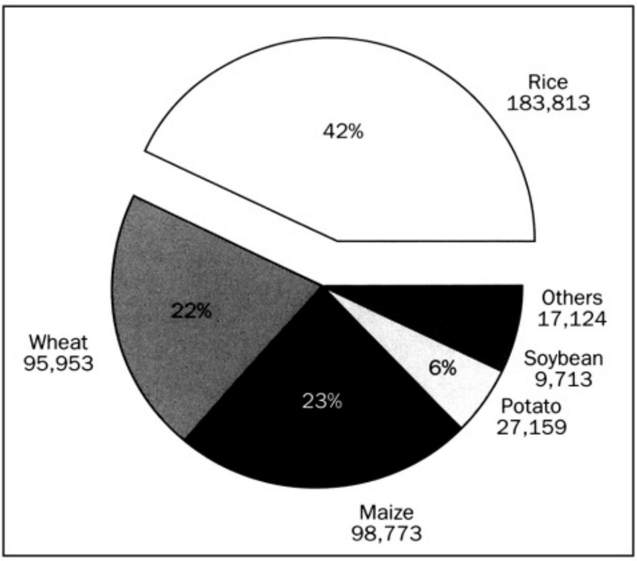



**Fig. 2.** Composition of grain output in thousands of tons.

induced innovation, which suggests that research resource allocation to a crop is a positive function of its size and price, Lin 1991a, 1992a.)

The history of China's organized agricultural research is rather short. Under the Nationalist government's rule from the 1920s to 1940s, a small decentralized system of research networks was established. This decentralized system continued after the socialist takeover in 1949. In 1957, the Chinese Academy of Agricultural Sciences was founded in Beijing. Meanwhile, each of the 29 provinces established its own academy of agricultural sciences. Each of the national and provincial academies has 10 to 30 independent research units. Most prefectures have also founded their own agricultural institutes. The division of labor within this three-level research system is rather broad, with considerable overlaps. The research institutes in the Chinese Academy of Agricultural Sciences emphasize basic and applied research with national significance, and are responsible for technical supervision and coordination of provincial programs. The institutes in provincial academies stress applied research in accordance with the ecological conditions of the province. Prefecture institutes mainly engage in crop selection and adaptive research. The institutes and their research projects at all three levels are mainly funded by government budgets at the corresponding levels.

Varietal improvement has been the focus of agricultural research in China from the very beginning. (I will only briefly summarize seed improvement research in this section. For other aspects of agricultural research and technological change in China, see Wiens 1982.) In the early 1950s, emphasis was given to the selection and promotion of the best local varieties. Meanwhile, new varieties of rice, wheat, cotton, maize, and other crops were also imported from abroad.[1] A major breakthrough in rice breeding occurred in 1964. In that year, China began full-scale distribution of fertilizer-responsive, lodging-resistant dwarf rice varieties with high-yield potential, two years before the release of IR8, the variety that launched the Green Revolution in other parts of Asia, by the International Rice Research Institute in the Philippines. At about the same time, hybrid maize and sorghum, improved cotton varieties, and new varieties of other crops were also released and promoted. The high-yielding varieties were accepted rapidly. A second major breakthrough in rice breeding occurred in 1976, when China became the first country, and for many years the only country, to commercialize the production of hybrid rice. (India and Vietnam also began commercializing hybrid rice production in the 1990s.) The innovation and commercial development of hybrid rice was heralded as the most important achievement in rice breeding in the 1970s (Barker and Herdt 1985). By 1979, the figures for area sown with high-yielding varieties were 80% for rice, 85% for wheat, 60% for soybeans, 75% for cotton, 70% for peanuts, and 45% for rape (Ministry of Agriculture 1989).

---

[1] In the 1950s and 1960s, 3,776 new varieties were imported from more than 30 different countries, and imports of new varieties continued to increase. In the 1970s, 43,674 varieties were imported from 85 countries and international organizations (Zhu Rong 1988). During the 1950s two problems were noted. First, whether borrowing from abroad or from the best seeds of a particular locality, borrowing without adaptation often resulted in crop failures. The second problem was that too much attention was given to high-yielding varieties requiring unusually favorable conditions, to the neglect of varieties that perform well under poor conditions (Wiens 1982).

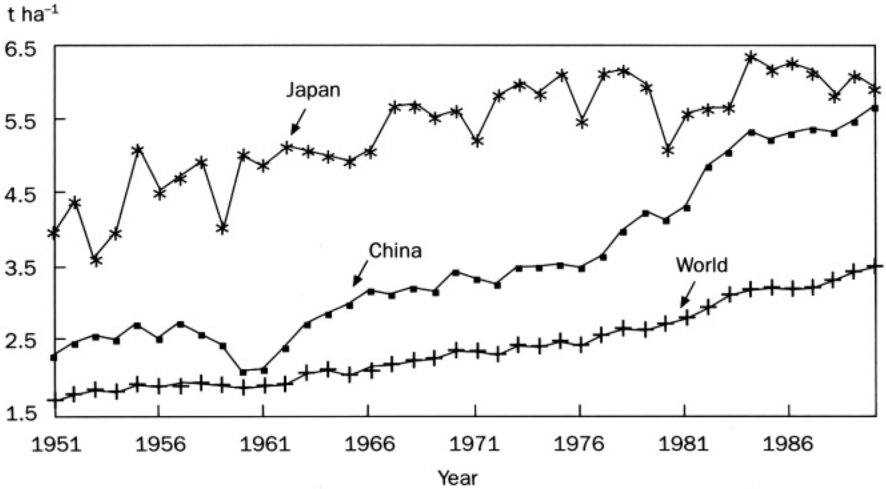



**Fig. 3.** Rice yield in China, Japan, and the world.

Figure 3 shows that the contribution of seed improvement research to the increase in rice yield in China is substantial. In the 1950s, yield was about 2.5 t $ha^{-1}$. (Yield in 1958-62 fell substantially below 2.5 t $ha^{-1}$. The sudden decline was attributable to the forced collectivization imposed in 1958, which distorted farmers' incentive structure. For a further discussion of this episode, see Lin [1990].) After the introduction of semidwarf varieties in the early 1960s, yield increased gradually to 3.5 t $ha^{-1}$ in the mid-1970s. Partly because of the introduction of hybrid rice in 1976 and partly because of the decollectivization of the farming system starting in 1979, yield increased swiftly from 3.5 t $ha^{-1}$ in the mid-1970s to 5.5 t $ha^{-1}$ in the mid-1980s (Lin 1991b, 1992b). China's rice yield in 1990 was about 60% higher than the world's average yield and close to that achieved by the most advanced countries, such as Japan (see Fig. 3). This achievement is especially significant because about half of the rice area in China grows two crops of rice each year instead of one.

One of the challenges to the rice research community in China is how to sustain the pace of the yield increase. Figures 4 and 5 show that the area sown to both grain and rice has been declining since the mid-1970s. This declining trend is most likely irreversible because it is a natural adjustment to the process of economic growth. But the demand for rice and grain is expected to rise continuously as the population and per capita incomes increase. Yield improvement is one of the major measures for meeting the increasing demand.

Several issues related to rice production are important to the research community:

1. What are the constraints to rice production in China?

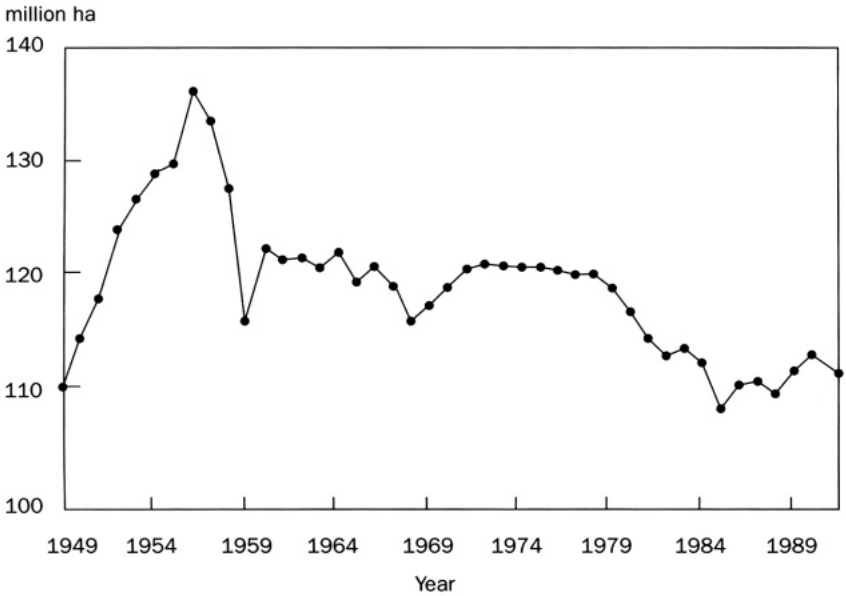



**Fig. 4.** Grain area in China.

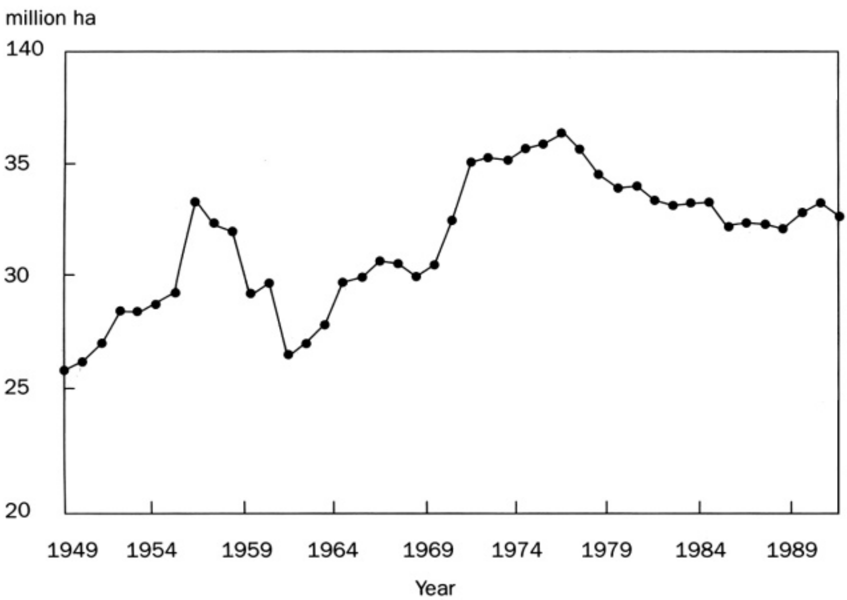



**Fig. 5.** Rice area in China.

2. What should be the priorities of China's rice research?

3. What is the best research strategy according to these priorities?

With support from the Rockefeller Foundation, a project on "Rice Research Priorities in China: Implications for a Biotechnology Initiative" is under way in China. This study hopes to shed light on these issues. Special attention is given to understanding the potential role of biotechnology in solving China's major rice production constraints.

This paper reports the findings on rice production constraints from an extensive study carried out in all rice production regions in China in October 1991-April 1992. The findings indicate that technical constraints constitute a substantial portion of estimated yield losses, and these technical constraints are concentrated on a few factors. But most of the constraints are soil- and weather-related. These constraints may not be handled easily by conventional methods of varietal improvement. Biotechnology, however, provides prospects for solving these problems. The rest of this paper is organized as follows: section two presents an overview of the rice production environment in China. Section three discusses briefly the methodology used in the survey. The major findings on the rice production constraints at the national level are summarized in section four. Detailed information on constraints in each ecological region is included in the same section. Some conclusions are presented in section five.

## The rice environment and natural conditions in China

China lies in the northern half of the eastern hemisphere. It is situated in the eastern part of Asia on the west coast of the Pacific Ocean. Its area covers approximately 9.6 million square kilometers, which is nearly one-fifteenth of the world's land. This makes China the third-largest country in the world, after Russia and Canada.

China's climate is greatly affected by its proximity to the sea on the east and south and by monsoon winds from the south. Cold winds sweeping in from the north and west, and the physical features of the landscape, all have an effect on, and are affected by, the climate. From south to north, the weather may be classified into tropical, subtropical, warm-temperate, temperate, and cold-temperate zones. Frost-free days vary from 365 in the tropical zone to fewer than 80 in parts of the north and west. From southeast to northwest, five moisture zones can be designated—humid, subhumid, semihumid, semiarid, and arid. In some of the humid southern coastal regions, annual precipitation exceeds 2,000 mm. In parts of the arid regions of the northwest, it is less than 100 mm.

Because most parts of China lie within the East Asian monsoon zone, the natural conditions, such as sunshine, temperature, and moisture, favor rice cultivation. Wherever rainfall is abundant or irrigation water is available, rice is produced. China extends from 18° to 53° north latitude. But the main rice producers are the areas south of the Qinling Mountains and the Huaihe River, which constitute 94% of the total national area sown to rice, and 93.6% of the total national rice production. Places suitable for rice production in China can be divided into six ecological zones according to different natural conditions and cropping systems: southern, central, southwestern,

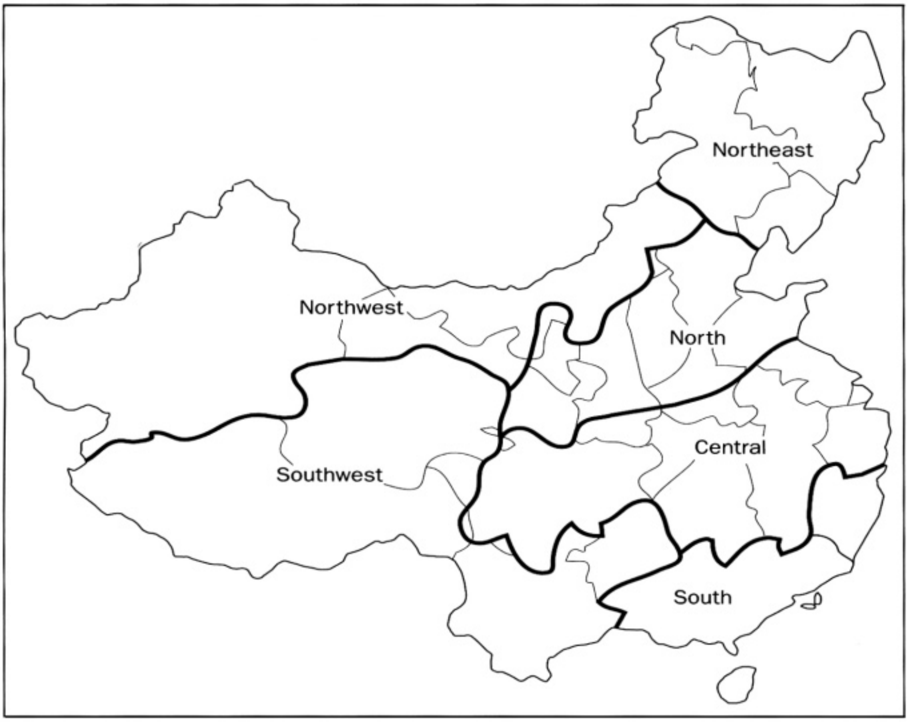



**Fig. 6.** Rice regions in China.

north, northeastern, and northwestern (Fig. 6). Table 1 explains the criteria for these ecological zones. This study covers all six ecological zones.

## Conceptual framework and survey methodology

The basic assumption of setting research priorities is that there exists a yield gap between potential yield and actual yield, or there is a possibility for increasing potential yield through research. The study of agricultural research priorities theoretically involves at least three issues: (1) identifying production constraints and the potential gains in production from overcoming these constraints, and identifying other likely sources of yield increase; (2) estimating the likelihood, possible time length, and cost of overcoming these constraints or identifying the likely sources of yield increase via alternative methods; and (3) determining the equity weights associated with each problem and each potential solution, and determining the net present value of equity-weighted expected costs and benefits for all possible problems. (For further discussions of the steps involved in setting research priorities, see Herdt and Riely 1987.) Some type of survey is required for obtaining relevant information for the first and second issues. The study reported here focuses mainly on production constraints.

**Table 1. Rice ecological zones in China.**

| Rice ecological zones | Criteria | | | |
|---|---|---|---|---|
| | Cropping system | Accumulated annual temperature of >10 °C (°C) | Precipitation (mm) | Aridity index[a] (E/r) |
| I. Humid tropical double-cropped rice zone in the south of China | Three maturing double-cropped rice | 26,500 | >1,000 | 4 |
| II. Humid single- and double-cropped rice zone in the center of China | Two and three maturing single- and double-cropped rice | 4,500–6,500 | >1,000 | 4 |
| III. Semihumid single-cropped rice zone in the north of China | One or two maturing single-cropped rice | 3,500–4,500 | >400 | 1–2 |
| IV. Semihumid early maturing single-cropped rice zone in the north of China | One maturing single-cropped rice | <3,500 | >400 | 1–2 |
| V. Arid single-cropped rice zone in south and northwest of China | One maturing single-cropped rice | 2,200–4,000 | <400 | >2 |
| VI. Humid single-cropped rice zone in southwest plateau of China | One maturing single-cropped rice | 3,000–6,500 | about 1,000 | <1 |

[a] E = the field's annual evaporation (mm), r = annual rainfall (mm).
Source: Chinese Academy of Agricultural Sciences. Zhongguo Daozuoxue (Rice cultivation in China). Beijing: Agricultural Press, 1986. p. 97.

According to work done at IRRI in the mid-1970s (IRRI 1977, 1979, De Datta et al 1978) and recent work by Widawsky and O'Toole (1990), the yield gap could be divided into two parts. Yield gap I is the difference between an experiment station's maximum yield and the potential average yield achievable under favorable conditions in a region. This yield gap arises from differences in varieties and the production environment that cannot be easily managed or eliminated by average farmers. Yield gap II is the difference between actual farm yields and yields attainable under favorable conditions with the given varieties. (The definitions for yield gaps I and II here are somewhat different from the definition used in IRRI's and Widawsky and O'Toole's studies. In China, the maximum yield on-farm is close to and sometimes even higher than the maximum yield at experiment stations. This is because research institutes are required to do field experiments in farmers' fields and the local government's special assistance to a few "window" farmers demonstrates the possibility of achieving higher yield in a region.) Yield gap II is caused by technological constraints and/or sociological constraints. (Sociological constraints may contribute to the existence of technical constraints. For example, a shortage of herbicides in the market [a sociological constraint] may be one of the causes of damage by weeds [a technical constraint]. But some sociological constraints may contribute to the yield loss independent of technical constraints, such as the impurity of seeds and bad water management.)

The first step in setting a research priority is to assess the yield gaps. In this study, we organized two separate surveys, one for research scientists at various rice research institutes and the other for agronomists in agricultural bureaus of the local government. For factors contributing to yield gap I, we relied on the judgment of research scientists because they have a good knowledge about the varietal differences between experimental varieties and field varieties and the environmental constraints that prohibited the experimental varieties from being used in field production. For factors contributing to yield gap II, knowledge about actual farm practices and local conditions that prevent field varieties from realizing potential yields is required. Therefore, for yield gap II, we relied on the judgment of agronomists in local governments who are responsible for grain production and technological extension in their localities.

## Agricultural bureaus' survey

In China, the government is organized into four hierarchical levels: the central government, the province, the prefecture, and the county. The agricultural bureau (ministry) at each level of government is responsible for agricultural production in the region under its jurisdiction. An agricultural bureau has divisions for crop production, crop protection, soil conservation, technology promotion, and field experiments. These divisions keep detailed records on information relevant to rice production constraints. A cost-effective way to obtain information on constraints for yield gap II is thus to conduct a survey of experienced agronomists in the agricultural bureaus. China is now jurisdictionally divided into 30 provinces (in addition to Taiwan), 364 prefectures, and 2,830 counties. Rice is grown in 29 of these 30 provinces. Information at the provincial level is too aggregated for analysis and there are too many rice-producing counties to survey. The study was therefore conducted at the prefecture level.

In the survey, we collected (1) historical data on sown area, total output, average yield, and the highest yields in fields, demonstration plots, and experimental plots; (2) the yield, area, and sources of the three leading varieties in the prefecture; (3) production losses caused by input constraints, pests, disease, weather/climate, and other technical problems; and (4) the estimated yield potential under favorable conditions for average farms in the prefecture. The information for early season, late-season, and single-season rice was collected separately.

The survey was carried out in two stages. In the first stage, a workshop was organized in each provincial capital to discuss the contents of the questionnaires. A leading agronomist from each prefecture was invited to participate in the workshop. After the workshop, the agronomists were responsible for organizing a team with about five agronomists in major fields in their bureau to answer the questionnaires collectively. After about a month, the leading agronomists were invited to participate in a second workshop to hand in the questionnaires and to discuss the findings with the research team. With the sanction of the Ministry of Agriculture and the State Science Commission, most prefectural bureaus gave full support to the survey. Table 2 summarizes statistics for the survey. For the nation as a whole, the numbers of prefectures producing early season, late-season, and single-season rice are 125, 126, and 224, respectively, and the numbers of prefectures with valid responses are 98, 97, and 152. In terms of rice area cultivated, the valid responses indicated that early season, late-season, and single-season rice represented 84.9%, 82.9%, and 79.8%, respectively, of total cultivated area.

## Research scientists' survey

We surveyed 193 rice research scientists nationwide with a full professorship or an associate professorship to obtain their judgments about the yield gaps and the factors that contribute to yield gap I. The list of these 193 scientists, who are actively involved in China's rice research, was provided by the Chinese Academy of Agricultural Sciences. We received 125 valid responses from 35 research institutes and 10 universities. Among the responses, 47.3% were from professors and 52.7% from associate professors. On the average, they have been involved in rice research for 26.8 years.

**Table 2. Summary statistics of the Agricultural Bureaus' Survey.**

| Item | Type of rice | Ecological zone | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Nation | South | Central | North | North-east | North-west | South west |
| Prefectures surveyed | Early | 125 | 39 | 80 | | | | 6 |
| | Late | 126 | 39 | 81 | 1 | | 1 | 4 |
| | Single | 224 | 17 | 88 | 47 | 31 | 18 | 23 |
| Valid responses | Early | 98 | 28 | 66 | | | | 4 |
| | Late | 97 | 28 | 66 | | | | 3 |
| | Single | 152 | 11 | 56 | 36 | 21 | 9 | 19 |
| Surveyed area (10,000 ha) | Early | 932.4 | 154.5 | 775.4 | | | | 2.5 |
| | Late | 967.2 | 169.5 | 796.9 | 0.9 | 0.02 | | 0.8 |
| | Single | 1,272.0 | 127.2 | 665.7 | 181.3 | 135.8 | 27.7 | 134.4 |
| Valid area/surveyed area (%) | Early | 84.9 | 93.3 | 83.2 | | | 98.6 | |
| | Late | 82.9 | 93.2 | 80.7 | | | 97.4 | |
| | Single | 79.8 | 95.7 | 76.3 | 97.5 | 65.3 | 20.1 | 85.5 |

The responses to the research scientists' survey were based on the scientists' personal experiences and judgment. This survey could not be as structured as the agricultural bureaus' survey. The responses to the latter survey were based mainly on official records and were supplemented by the judgment of agronomists with extensive knowledge about rice production in the localities where they work. Therefore, we used an open questionnaire for this survey. Research scientists were asked to provide personal judgments for factors that contribute to yield gap I. They were instructed to list the factors about which they had sufficient knowledge and not to comment on factors that they did not know much about. As a result, the factors listed by each scientist differ. The statistics show that the average number of factors listed by the scientists is 8.7 for early season rice, 9.4 for late-season rice, and 9.2 for single-season rice. About 50 factors are mentioned; of these, 18 are mentioned most frequently (Table 3).

## Rice production constraints in China

The purpose of the above two surveys was to obtain information about the estimations on yield gaps and factors contributing to the gaps. The rest of this paper discusses our findings.

**Table 3. Summary statistics of Research Scientists' Survey by type of rice.**

| | Early season | Late season | Single season |
|---|---|---|---|
| Number of valid responses: | 62 | 53 | 56 |
| Constraints | Frequency of responses (%) | | |
| Variety-related constraints | | | |
| 1. Canopy architecture | 48.4 | 58.5 | 44.6 |
| 2. Photosynthetic rate | 50.0 | 50.9 | 48.2 |
| 3. Growth duration | 61.3 | 56.6 | 66.1 |
| 4. Efficiency of nutrition transformation | 37.1 | 37.7 | 35.7 |
| 5. Panicle morphology | 17.7 | 15.1 | 12.5 |
| 6. Tillering ability | 33.9 | 32.1 | 30.4 |
| 7. 1,000-grain weight | 8.1 | 9.4 | 10.7 |
| 8. Spikelet fertility | 16.2 | 20.7 | 19.7 |
| 9. Vigor of roots | 6.5 | 0.0 | 7.1 |
| 10. Grain to straw ratio | 8.1 | 5.7 | 1.8 |
| 11. Filled spikelet percentage | 1.6 | 3.8 | 1.8 |
| Environment - related constraints | | | |
| 1. Duration of sunshine | 43.5 | 49.1 | 50.0 |
| 2. Accumulated heat units | 35.5 | 34.0 | 25.0 |
| 3. Soil conditions | 32.3 | 30.2 | 26.8 |
| 4. Diurnal temperature variation | 21.0 | 17.0 | 19.6 |
| 5. Frost-free period | 1.6 | 1.9 | 1.8 |
| 6. Relative humidity | 3.2 | 3.8 | 3.6 |
| 7. Other unfavorable climate | 8.1 | 5.7 | 8.9 |

## Yield gaps

To assess the yield gaps, the respondents for the Agricultural Bureaus' Survey were asked to provide information about the maximum yields at experiment stations and on the plots of experienced farmers in the past 10 years in their prefectures. Table 4 summarizes the information on the maximum yields for each type of rice in the farmers' fields and at the experiment stations reported in the survey and the averages of the maximums reported by each agricultural bureau.

Table 4 shows that the reported maximum yields for experiment stations for early season, late-season, and single-season rice are 14,700, 12,307, and 17,577 kg ha$^{-1}$, respectively. The maximum yield in farmers' fields is close to the maximum yield at the experiment stations. In some cases, the former is higher than the latter for three reasons. First, the varieties grown at the experiment stations were still in the trial stage, and some of them might not be adaptable to the local environments. Second, farmers with the highest yields often received advice and help from the experiment station, and their yields can be viewed as the yields of on-farm experimentation. Third, because of the official campaign of "reaching 15 ha$^{-1}$" (1 t mu$^{-1}$), the local government often gives a few "showcase" farmers priorities in the allocation of chemical fertiliz-

**Table 4. The maximum yield (kg ha$^{-1}$) reported in the Agricultural Bureaus' Survey.**

| Year | Early season | | Late-season | | Single-season | |
|---|---|---|---|---|---|---|
| | Maximum | Average | Maximum | Average | Maximum | Average |
| Farmers' fields | | | | | | |
| 1980 | 11,364 | 7,484 | 10,553 | 6,885 | 12,885 | 7,734 |
| 1981 | 12,155 | 7,566 | 10,305 | 6,844 | 15,441 | 8,120 |
| 1982 | 11,486 | 7,767 | 11,423 | 7,116 | 14,159 | 8,465 |
| 1983 | 11,363 | 7,893 | 11,460 | 7,463 | 15,215 | 8,816 |
| 1984 | 11,708 | 8,136 | 11,483 | 7,607 | 16,424 | 9,177 |
| 1985 | 12,825 | 8,070 | 11,627 | 7,692 | 15,150 | 8,967 |
| 1986 | 11,250 | 8,166 | 12,378 | 7,826 | 15,750 | 9,363 |
| 1987 | 11,880 | 8,349 | 10,875 | 7,860 | 15,344 | 9,506 |
| 1988 | 11,558 | 8,499 | 11,316 | 8,022 | 15,450 | 9,782 |
| 1989 | 11,862 | 8,619 | 12,083 | 8,324 | 15,885 | 9,969 |
| 1990 | 12,711 | 8,832 | 12,375 | 8,417 | 15,345 | 10,287 |
| Experimental plots | | | | | | |
| 1980 | 11,708 | 7,944 | 10,856 | 7,202 | 14,153 | 8,477 |
| 1981 | 10,911 | 7,859 | 10,013 | 7,239 | 14,441 | 8,736 |
| 1982 | 11,970 | 8,109 | 10,508 | 7,404 | 14,646 | 9,057 |
| 1983 | 11,421 | 8,048 | 10,575 | 7,619 | 16,131 | 9,245 |
| 1984 | 13,995 | 8,523 | 12,188 | 7,829 | 15,686 | 9,620 |
| 1985 | 11,310 | 8,346 | 11,841 | 8,024 | 15,585 | 9,710 |
| 1986 | 12,464 | 8,411 | 10,377 | 8,081 | 15,893 | 9,834 |
| 1987 | 14,700 | 8,594 | 12,308 | 8,280 | 17,012 | 10,080 |
| 1988 | 12,645 | 8,595 | 11,357 | 8,270 | 17,577 | 10,182 |
| 1989 | 11,760 | 8,853 | 11,535 | 8,516 | 15,747 | 10,406 |
| 1990 | 11,985 | 8,976 | 11,910 | 8,808 | 16,821 | 10,853 |

**Table 5. Highest yields (kg ha $^{-1}$) estimated by agronomists and scientists.**

| | Highest yield | | Average highest yield | |
|---|---|---|---|---|
| | Agronomists | Scientists | Agronomists | Scientists |
| Early season rice | 14,700 | 13,695 | 9,678 | 9,705 |
| Late-season rice | 12.378 | 16,815 | 9,246 | 9,773 |
| Single-season rice | 17,577 | 18,075 | 11,363 | 11,888 |

ers and other inputs in order to show that it is possible to reach this campaign goal. A correlation analysis indicates that the maximum yield at experiment stations and on farms in a prefecture is highly correlated. The correlation coefficient reaches .74. Therefore, the maximum yield on farms in China has the property of the maximum yield at experiment stations in other countries.

In the Research Scientists' Survey, we also asked each scientist to tell us the highest-ever experimental yield that they knew of or had heard of. The highest experimental yields obtained from this survey are very close to the highest yields reported in the Agricultural Bureaus' Survey. Table 5 lists the maximum yield for each type of rice reported in these two surveys and the average of the highest yields given by agricultural bureaus and research scientists. These two sets of figures, especially the averages, are very close to each other. But except for the early season rice, the highest observed yields and the averages reported by the research scientists are higher than those reported by the agricultural bureaus. This is expected because an agricultural bureau's report is based on observations over the past 10 years in its prefecture, but a research scientist's report is not limited to observations in the past 10 years and his or her experiments might not be known by the agronomists in the agricultural bureaus. To calculate yield gap I, we will use the highest yield reported in the two surveys, which represents the biological potential that can be realized under existing scientific knowledge. The maximum yield that will be used is thus 14,700 kg ha$^{-1}$ for early season rice, 16,815 kg ha$^{-1}$ for late-season rice, and 18,075 kg ha$^{-1}$ for single-season rice.

The second step in estimating yield gaps I and II is to obtain the estimation of potential yield under favorable conditions for an average farm in a prefecture. This information is available in the Agricultural Bureaus' Survey. The difference between the maximum yield and potential yield for an average farm represents yield gap I and the difference between the potential yield and actual yield is yield gap II. The means of the estimated potential are 7,676, 7,592, and 9,342 kg ha$^{-1}$ for early season, late-season, and single-season rice. The avera`ge actual yield in the 1990s is 5,112 kg ha$^{-1}$ for early season rice, 4,611 kg ha$^{-1}$ for late-season rice, and 5,951 kg ha$^{-1}$ for single-season rice. The regression analyses in Table 6 show that a prefecture's estimation of potential yield achievable by average farms under favorable conditions in that prefecture is predominantly a function of the prefecture's actual average yield. The maximum yields at experiment stations in a prefecture in terms of both the 1990 level and

**Table 6. Regression analyses of expected yield potential.**

| Factor | Early season rice[a] | Late-season rice | Single-season rice |
|---|---|---|---|
| Constant | 2,727.90<br>4,955.14<br>(2.15)*<br>(3.79)*** | 2,943.99<br>5,253.94<br>(2.19)*<br>(4.47)*** | 4,485.53<br>6,130.18<br>(4.08)***<br>(4.57)*** |
| Average farm yield in 1990 | .55<br>.70<br>(3.71)***<br>(4.11)*** | .56<br>.54<br>(3.46)***<br>(4.38)*** | .65<br>.64<br>(4.12)***<br>(4.08)*** |
| Highest farm yield in 1990 | .02<br>(.13) | –.28<br>(1.70) | –.02<br>(.16) |
| Highest exp. yield in 1990 | .23<br>(1.38) | .27<br>(1.61) | .11<br>(1.01) |
| Av highest farm yield 1981-90 | .10<br>(.50) | –.03<br>(.02) | –.0003<br>(.02) |
| Av highest exp. yield 1981-90 | .14<br>(.66) | –.06<br>(.26) | –.04<br>(.23) |
| $\bar{R}^2$ | .17<br>.17 | .17<br>.12 | .18<br>.12 |
| Observations (no.) | 85<br>69 | 70<br>135 | 84<br>104 |

[a] The numbers in parentheses indicate the absolute values of t-statistlcs. *, **, *** indicate respectively the statistical significance at .05, .01, and .001 levels of confidence.

the average level of 1981-90 do not have significant effects on a prefecture's estimation of potential yield. Similarly, the maximum yield on farms in a prefecture does not have any significant effect on the prefecture's estimation either. This evidence strongly supports the argument that most respondents view the difference between the maximum yield at the experiment station or on the farm and their estimation of potential yield as nontransferable, and the difference between the estimation and the actual yield as transferable. Therefore, the distinction between yield gap I and yield gap II is valid.

Table 7 reports the information on yield gaps I and II based on the information on maximum yield, average estimated potential yield, and average actual yield. For the nation as a whole, yield gap I for early season rice is 7,024 kg $ha^{-1}$, for late-season rice 9,223 kg $ha^{-1}$, and for single-season rice 8,733 kg $ha^{-1}$, whereas yield gap II for early season rice is 2,564 kg $ha^{-1}$, for late-season rice 2,981 kg $ha^{-1}$, and for single-season rice 3,391 kg $ha^{-1}$. From the comparison of yield gaps I and II, we find that the non-transferable yield gap I is substantially larger than the transferable yield gap II for each type of rice. Yield gap I indicates the varietal and environmental differences between experimental plots and farmers' fields. These differences cannot be easily

Table 7. Yield gaps I and II in kg ha$^{-1}$.

| Factor | Early season rice | Late-season rice | Single-season rice |
|---|---|---|---|
| Maximum yield[a] | 14,700 | 16,815 | 18,075 |
| Average estimated potential farm yield | 7,676 | 7,592 | 9,342 |
| Average actual farm yield | 5,112 | 4,611 | 5,951 |
| Yield gap I | 7,024 | 9,223 | 8,733 |
| Yield gap II | 2,564 | 2,981 | 3,391 |

[a]Maximum yield refers to the highest observation of the maximum yield in the Research Scientists' Survey or the highest maximum in the Agricultural Bureaus' Survey.

eliminated or managed by an average farmer. But biotechnology offers a possibility for transferring higher yield without dependence on some of the management technologies previously needed for realizing high yields. Therefore, biotechnology may provide prospects for major yield increases in China.

## Technical constraints

In the study, we attempted to survey in depth the factors that contribute to yield gaps I and II. Research scientists have a better knowledge about the varietal differences between those that produced the maximum yield on experimental plots and the ones that are widely used in farmers' fields and the environmental constraints that prevent the maximum yield for experimental varieties to be extended to farmers' fields. Therefore, our analysis of yield gap I is based on the information provided by research scientists. For yield gap II, our analysis relies on the information provided by agronomists at the prefectural agricultural bureaus.

*Yield gap I constraints.* In the Research Scientists' Survey, we first provided the scientists with information about the average potential yield for each type of rice, obtained from the Agricultural Bureaus' Survey. We then asked them to list the factors that contribute to the yield gap between the maximum and the average potential yield and estimate the percentage of this yield gap that can be explained by each factor listed. We assumed that if a research scientist did not mention a certain factor, that factor was not important in this scientist's viewpoint. Therefore, we assigned a value of zero to that factor. The percentage of yield gap I explained by each factor is thus a simple average of the estimated percentage reported by the research scientists. We can then use the average percentage and the estimated yield gap I to infer how large the yield loss is due to each of the individual factors. Tables 8–10 report the results of this exercise.

From the tables, we find that for all three types of rice, the 11 variety-related factors explain about 35% of the estimated yield gap I, the 7 environment-related factors explain about 20%, and about 45% of the yield gap is unaccounted for. Among the 11 variety-related factors, canopy architecture, photosynthetic rate, and growth duration are the most important ones for all three types of rice. These three factors respectively account for 24.63%, 22.86%, and 22.83% of yield gap I for early season,

**Table 8. Yield gap I for early season rice.**

| Constraints | Percentage explained | Loss attributed (kg ha$^{-1}$) |
|---|---|---|
| Yield gap I | 100.00 | 7,022 |
| *Variety-related constraints* | 37.99 | 2,668 |
| 1. Canopy architecture | 5.81 | 408 |
| 2. Photosynthetic rate | 7.56 | 531 |
| 3. Growth duration | 11.26 | 791 |
| 4. Efficiency of nutrition transformation | 3.58 | 251 |
| 5. Panicle morphology | 3.05 | 214 |
| 6. Tillering ability | 2.77 | 195 |
| 7. 1,000-grain weight | 0.74 | 52 |
| 8. Spikelet fertility | 1.81 | 127 |
| 9. Vigor of roots | 0.44 | 31 |
| 10. Grain to straw ratio | 0.65 | 46 |
| 11. Filled spikelet percentage | 0.32 | 22 |
| *Environment-related constraints* | 19.78 | 1,388 |
| 1. Duration of sunshine | 5.95 | 418 |
| 2. Accumulated heat units | 5.66 | 398 |
| 3. Soil conditions | 3.68 | 258 |
| 4. Diurnal temperature variation | 2.27 | 159 |
| 5. Frost-free period | 0.32 | 22 |
| 6. Relative humidity | 0.32 | 22 |
| 7. Other unfavorable climate | 1.58 | 111 |
| Unexplained | 42.23 | 2,966 |

**Table 9. Yield gap I for late-season rice.**

| Constraints | Percentage explained | Loss attributed (kg ha$^{-1}$) |
|---|---|---|
| Yield gap I | 100.00 | 9,220 |
| *Variety-related constraints* | 37.10 | 342 |
| 1. Canopy architecture | 7.75 | 715 |
| 2. Photosynthetic rate | 7.79 | 718 |
| 3. Growth duration | 7.32 | 675 |
| 4. Efficiency of nutrition transformation | 3.70 | 341 |
| 5. Panicle morphology | 2.49 | 230 |
| 6. Tillering ability | 2.62 | 242 |
| 7. 1,000-grain weight | 1.13 | 104 |
| 8. Spikelet fertility | 2.64 | 243 |
| 9. Vigor of roots | 0.45 | 42 |
| 10. Grain to straw ratio | 0.36 | 33 |
| 11. Filled spikelet percentage | 0.85 | 78 |
| *Environment-related constraints* | 18.58 | 1,712 |
| 1. Duration of sunshine | 7.26 | 670 |
| 2. Accumulated heat units | 4.51 | 416 |
| 3. Soil conditions | 3.02 | 276 |
| 4. Diurnal temperature variation | 1.92 | 177 |
| 5. Frost-free period | 0.57 | 53 |
| 6. Relative humidity | 0.38 | 35 |
| 7. Other unfavorable climate | 0.92 | 85 |
| Unexplained | 44.32 | 4,087 |

**Table 10. Yield gap I for single-season rice.**

| Constraints | Percentage explained | Loss attributed (kg $ha^{-1}$) |
|---|---|---|
| Yield gap I | 100.00 | 8,729 |
| *Variety-related constraints* | 35.04 | 3.061 |
| 1. Canopy architecture | 7.37 | 644 |
| 2. Photosynthetic rate | 6.05 | 528 |
| 3. Growth duration | 9.41 | 822 |
| 4. Efficiency of nutrition transformation | 3.11 | 272 |
| 5. Panicle morphology | 2.18 | 190 |
| 6. Tillering ability | 2.64 | 231 |
| 7. 1,000-grain weight | 0.98 | 86 |
| 8. Spikelet fertility | 2.25 | 196 |
| 9. Vigor of roots | 0.73 | 64 |
| 10. Grain to straw ratio | 0.14 | 12 |
| 11. Filled spikelet percentage | 0.18 | 16 |
| *Environment-related constraints* | 18.78 | 1,636 |
| 1. Duration of sunshine | 8.80 | 766 |
| 2. Accumulated heat units | 3.05 | 266 |
| 3. Soil conditions | 3.16 | 276 |
| 4. Diurnal temperature variation | 2.57 | 224 |
| 5. Frost-free period | 0.14 | 12 |
| 6. Relative humidity | 0.45 | 39 |
| 7. Other unfavorable climate | 0.61 | 53 |
| Unexplained | 46.18 | 4,032 |

late-season, and single-season rice. Among the 7 environment-related factors, duration of sunshine, accumulated heat units, and soil conditions are the most important ones. These three factors respectively account for 15.29%, 14.79%, and 15.01% of yield gap I for early season, late-season, and single-season rice.

The survey shows that variety-related factors are more important than environment-related factors in accounting for yield gap I. Environmental factors cannot be easily changed. But improvement in a variety's resistance to an adverse environment will reduce the environmental impact on yield. Therefore, yield gap I may be narrowed by making the experimental varieties, which have the desirable variety-related characteristics, available for extension to farmers' fields or by giving the available varieties a higher resistance to an adverse environment.

About 45% of yield gap I for all three types of rice is not accounted for by variety-related and environment-related factors. There are three explanations for this result: (1) many scientists attribute the difference between the maximum experimental yield and the potential farm yield to differences in crop management, (2) some scientists believe that the highest experimental yield for each type of rice is overreported, and (3) some scientists mention that some synthesized effect cannot be broken down into individual factors.

*Yield gap II constraints.* Yield gap II is the difference between the actual farm yield in a prefecture and potential farm yield under favorable conditions in that pre-

**Table 11. Yield gap II in kg ha$^{-1}$.**

| Constraints | Early season rice (% loss) | | Late-season rice (% loss) | | Single-season rice (% loss) | |
|---|---|---|---|---|---|---|
| | Explained | Attributed | Explained | Attributed | Explained | Attributed |
| Yield gap II | 100.00 | 2,564 | 100.00 | 2,981 | 100.00 | 3,391 |
| Technical constraints | 44.93 | 1,152 | 40.66 | 1,212 | 43.14 | 1,463 |
| Soil | 22.66 | 581 | 20.03 | 597 | 18.72 | 635 |
| Disease | 2.69 | 69 | 1.78 | 53 | 2.60 | 88 |
| Pests | 1.52 | 39 | 1.64 | 49 | 2.71 | 92 |
| Weather | 15.72 | 403 | 14.96 | 446 | 16.43 | 557 |
| Other | 2.34 | 60 | 2.25 | 67 | 2.68 | 91 |
| Unexplained | 55.07 | 1,412 | 59.34 | 1,769 | 56.86 | 1,928 |

fecture. When we analyze factors contributing to yield gap II, the varieties are taken as a given. Because knowledge about rice production at a specific location is required, the analysis for yield gap II is based on the information obtained from the Agricultural Bureaus' Survey. Yield gap II can be explained by socioeconomic constraints or technological constraints. We focus in the study on technological constraints. Following the conventions of Widawsky and O'Toole (1990), technical constraints are classified into five categories: adverse soils, diseases, insects, adverse climate/weather, and others. Respondents were instructed to answer the questionnaire based on the historical records in their prefectures. Table 11 summarizes the results of the survey.

The estimations of the total losses in the nation as a whole that can be accounted for by the constraints listed in the questionnaire are 1,152 kg ha$^{-1}$ for early season rice, 1,212 kg ha$^{-1}$ for late-season rice, and 1,463 kg ha$^{-1}$ for single-season rice. They account for 45%, 41%, and 43% of yield gap II for early season, late-season, and single-season rice, respectively. The rest of yield gap II is caused by socioeconomic factors or technical factors not listed in the questionnaire. Important socioeconomic factors include seed impurity, seed degeneration, bad management, bad extension service, and so on.

As a part of the yield loss caused by technical constraints, soil- and weather-related factors make up the lion's share. The soil-related factors can be subdivided into problems arising from soil type and from soil fertility. In turn, these can be broken down further. Similarly, the weather-related constraints can be subdivided into submergence, drought, cold, heat, typhoon, hail, and snow, and each of these can be further divided into the seedling, vegetative, anthesis, and whole periods. Pests, diseases, and other problems can all be broken down into more detailed factors. To set the research agenda, a detailed breakdown is required.

The estimated yield loss from individual constraints for each type of rice is calculated in the following equation: Estimated yield $\text{loss}_i = (\Sigma_j$ average yield loss $81–90_{ij})/(\Sigma_j$ average sown area $81–90_j)$, where $i$ indicates a constraint and $j$ indicates a prefecture. The estimation for the average yield loss is primarily based on official records. When these are not available, agronomists are asked to make an estimation according to their observations. Both the official records and individual observations should contain objective elements. The absolute magnitude of the estimated yield loss from an individual constraint is not exact. But the relative magnitudes of the estimated yield losses among different constraints provide a basis for assessing the relative contribution of these constraints to the yield gap.

Table 12 reports estimated yield losses nationally from the top 20 individual technical constraints. For early season rice, the top 10 constraints contributed to 60% of the total estimated yield losses from technical constraints. Of the top 10 constraints, 7 are related to soil conditions. The other 3 are related to weather. The top 11 to 20 constraints represented another 24% of estimated yield losses from technical constraints. These 10 constraints were spread among weather, diseases, soil, and weeds. For late-season rice, the top 10 constraints contributed to 68% of the total estimated yield losses from technical constraints. Again, adverse soil conditions and weather-related factors dominated the top 10 list. The top 11 to 20 constraints represented another 17% of the estimated yield losses. Sheath blight, weeds, and rodents are on this list. The rest are again related to weather and soil conditions. For the single-season rice, the top 10 constraints contributed to 59% of estimated yield losses and another 22% was caused by the top 11 to 20 constraints. Adverse soil and weather conditions predominate on the list.

Table 12 shows that, overall, the most important technical constraints are deficiencies in nitrogen, phosphorus, potassium, organic contents, and trace elements. Two reasons may help explain this. On the one hand, it reflects the long history of intensive rice cropping in China. Therefore, soil fertility has been depleted and cannot be recovered by natural processes. On the other hand, it reflects the high fertilizer-responsiveness of the current varieties. It is possible to increase yield simply by increasing the application of fertilizers. But whether or not farmers have the incentive to do so depends on the relative prices of rice and fertilizers.

Cold waterlogged soil is also a major cause of yield losses. This may be because (1) rice is grown only in areas with irrigation and (2) a substantial portion of rice fields is located in hilly areas.

The second most important cause of yield losses is related to weather, including drought, submergence, cold, and heat at the seedling, vegetative, and anthesis periods, and lodging caused by wind and storms. For the various rice diseases and pests, only sheath blight and striped stem borer are among the top 20 constraints. This phenomenon may be explained by two reasons. First, rice yield in China is among the highest in the world. Most constraints that may predominate in a low-yielding country but can be controlled by conventional methods have been eliminated in China. Second, rice production is still subject to adverse weather in China. Variations in

**Table 12. The top 20 constraints nationally.**

| Item | Early season rice | Late-season rice | Single-season rice |
|---|---|---|---|
| Total loss (kg $ha^{-1}$) | 1,152 (100%) | 1,212 (100%) | 1,463 (100%) |
| Sum of top 10 constraints | 683 (60%) | 813 (68%) | 860 (59%) |
| Sum of top 20 losses/total loss | 967 (84%) | 1,025 (85%) | 1,185 (81%) |

| Early season rice | | Late-season rice | |
|---|---|---|---|
| 1. Potassium deficiency | 145 | 1. Potassium deficiency | 181 |
| 2. Phosphorus deficiency | 90 | 2. Cold at anthesis | 101 |
| 3. Nitrogen deficiency | 72 | 3. Nitrogen deficiency | 86 |
| 4. Cold waterlogged soil | 69 | 4. Drought at anthesis | 82 |
| 5. Organic matter deficiency | 68 | 5. Phosphorus deficiency | 77 |
| 6. Cold at seedling period | 63 | 6. Organic matter deficiency | 75 |
| 7. Flood | 50 | 7. Drought at vegetative period | 62 |
| 8. Acidity | 47 | 8. Cold waterlogged soil | 54 |
| 9. Trace elements deficiency | 42 | 9. Flood | 53 |
| 10. Drought at anthesis | 38 | 10. Acidity | 42 |
| 11. Sheath blight | 37 | 11. Trace elements deficiency | 42 |
| 12. Heat at anthesis | 36 | 12. Sheath blight | 27 |
| 13. Lodging from wind and storms | 34 | 13. Weeds | 22 |
| 14. Submergence at anthesis | 32 | 14. Drought at seedling period | 20 |
| 15. Drought at vegetative period | 31 | 15. Lodging from wind, storms | 19 |
| 16. Swamp soil | 29 | 16. Submergence at veg. period | 18 |
| 17. Cold at vegetative period | 25 | 17. Swamp soil | 17 |
| 18. Rain at harvest | 23 | 18. Submergence at seedling period | 17 |
| 19. Rice blast | 19 | 19. Submergence at anthesis | 15 |
| 20. Weeds | 18 | 20. Rats | 15 |

| Single-season rice | |
|---|---|
| 1. Organic matter deficiency | 109 |
| 2. Cold waterlogged soil | 105 |
| 3. Nitrogen deficiency | 104 |
| 4. Phosphorus deficiency | 100 |
| 5. Potassium deficiency | 95 |
| 6. Flood | 90 |
| 7. Drought at anthesis | 82 |
| 8. Drought at vegetative period | 70 |
| 9. Trace elements shortage | 54 |
| 10. Cold at anthesis | 51 |
| 11. Submergence at anthesis | 42 |
| 12. Rain at harvest | 40 |
| 13. Drought at seedling period | 39 |
| 14. Sheath blight | 39 |
| 15. Weeds | 38 |
| 16. Cold at seedling period | 30 |
| 17. Acidity | 28 |
| 18. Rats | 25 |
| 19. Striped stem borer | 23 |
| 20. Lodging from wind, storms | 22 |

weather conditions can cause a more than 5% variation in average yield nationwide from year to year.

## Conclusions

This paper reports the research design, survey procedure, and findings from a study for the project "Rice Research Priorities in China: Implications for a Biotechnology Initiative." As a first step in setting research priorities, the study used questionnaire surveys to obtain information on the highest experimental yields and actual farm yields and to elicit estimates of potential farm yield under favorable conditions from scientists at rice research institutions and experienced agronomists at prefectural bureaus of agriculture. The difference between the highest experimental yield and potential farm yield under favorable conditions is referred to as yield gap I, which arises from differences in experimental varieties and farm varieties and between the environment at experiment stations and in farm fields. The difference between potential farm yield and actual farm yield is referred to as yield gap II. This gap reflects biological, soil and water, and socioeconomic constraints. Yield gap II can be removed under favorable conditions. The survey also attempted to identify individual constraints that contribute to yield gaps I and II.

For the nation, the highest experimental yields are 14,700, 16,815, and 18,075 kg $ha^{-1}$, respectively, for early season, late-season, and single-season rice. They are, respectively, 188%, 264%, and 203% higher than the average actual farm yields in 1990. Most of the gap between the highest experimental yield and actual farm yield belongs to yield gap I, which arises from differences in the characteristics of the experimental varieties and field varieties and from nontransferable environmental factors. A major goal of using biotechnology in varietal improvement is to transfer the characteristics of higher yield to farm varieties without depending on environmental factors and management technologies. Research in biotechnology is likely to provide a vital vehicle for tapping into the potential sources of yield increases for gap I.

For the losses from yield gap II, the predominant factors are related to adverse soil conditions and adverse weather or climate. Diseases and pests do not cause major yield losses in China. This finding is consistent with the fact that the rice yield in China is almost the highest in the world. Most losses from factors that can be controlled by conventional methods have been managed. Biotechnology may also provide a way to solve constraints arising from low soil fertility, adverse soil conditions, and adverse weather or climate.

This paper represents a first step toward setting rice research priorities. From the findings, we can conclude that biotechnology research is important for further increasing rice yield in China. From this study, we find that research can focus on a few well-defined constraints. For closing yield gap I, research should concentrate on improving a rice variety's canopy architecture, photosynthetic rate, and growth duration, and improving plant ability to resist unfavorable duration of sunshine, accumulated heat, and soil conditions. For closing yield gap II, the main areas for biotechnology research include low soil fertility; cold waterlogged and acid soil; drought, submergence, heat, and cold at the seedling, vegetative, and anthesis periods; lodging; weeds; sheath blight; and stem borer.

## References


Barker R, Herdt RW. 1985. The rice economy of Asia. Washington, D.C. (USA): Resources for the Future.

De Datta SK, Gomez KA, Herdt RW, Barker R. 1978. A handbook on the methodology for an integrated experiment: survey on rice yield constraints. Los Baños (Philippines): International Rice Research Institute.

Herdt RW, Riely FZ. 1978. International rice research priorities: implications for biotechnology initiatives. Prepared for the Rockefeller Foundation Workshop on Allocating Resources for Developing Country Agricultural Research, Belagio, Italy, July 6-10, 1987.

IRRI (International Rice Research Institute). 1977. Constraints to high yields on Asian rice farms: an interim report. Los Baños (Philippines): International Rice Research Institute.

IRRI (International Rice Research Institute). 1979. Farm level constraints to high rice yields in Asia: 1974-1977. Los Baños (Philippines): International Rice Research Institute.

Lin JY. 1990. Collectivization and China's agricultural crisis in 1959-1961. J. Polit. Econ. 9811228-1252.

Lin JY. 1991a. Public research resource allocation in Chinese agriculture: a test of induced technological innovation hypotheses. Econ. Dev. Cult. Change 40:55-73.

Lin JY. 1991b. The household responsibility system reform and the adoption of hybrid rice in China. J. Dev. Stud. 363.53-372.

Lin JY. 1992a. Hybrid rice innovation: a study of market-demand induced technological innovation in a centrally planned economy. Rev. Econ. Stat. 74:14-20.

Lin JY. 1992b. Rural reforms and agricultural growth in China. Am. Econ. Rev. 82:34-5 1.

Ministry of Agriculture, Planning Bureau. 1989. Zhongguo nongcun jingji ziliao tongji daquan, 1949-1986 (A comprehensive book of China rural economic statistics, 1949-1986). Beijing: Agricultural Press.

Widawsky DA, O'Toole JC. 1990. Prioritizing the rice biotechnology research agenda for eastern India. New York: The Rockefeller Foundation.

Wiens TB. 1982. Technological change. In: Barker R, Sinha R, editors. The Chinese agricultural economy. Boulder, Colo. (USA): Westview.

Zhu Rong, editor. 1988. Dangdai zhongguo de nongzuowuye (The science of crops in modern China). Beijing: China Social Sciences Press.


## Notes


Author's address: Department of Economics, School of Business and Management, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong. jlin@pku.edu.cn



Citation: Dowling NG, Greenfield SM, Fischer KS, editors. 1998. Sustainability of rice in the global food system. Davis, Calif. (USA): Pacific Basin Study Center, and Manila (Philippines): International Rice Research Institute.

CHAPTER 21

# Priorities and opportunities of rice production and consumption in India for self-sufficiency

R.S. Paroda

From 1965 through 1995, India surged forward in its national rice production from a situation of food deficit to one of sustainable surplus. This achievement was made possible primarily because of the adoption of high-yielding varieties, the extension of irrigation, and expansion of the area under rice cultivation. The highest growth rate in rice productivity occurred between 1985 and 1995 because of the joining of the eastern region of the country with the rapidly advancing western region and the steadily growing southern region. To sustain this self-sufficiency and meet the food requirements of millions of people, India needs at least a 3% $yr^{-1}$ productivity growth rate to achieve rice production targets of 95 and 135 million tons by the years 2000 and 2020, respectively. This growth rate can be achieved by (1) using available technology while reducing the constraints to rice production, (2) increasing genetic yield and stabilizing productivity through hybrid technology, and (3) exploiting abundant untapped opportunities in potential rice-growing environments.

Because inventory management is essential from the natural resource base to the distribution system, information systems must support national and state decision making on the food supply. National decision making currently emphasizes international markets, buffer stocks, and operational food policies, while state decision making stresses local prices, market regulations, seasonal weather aberrations, production trends, and infrastructure for distribution.

Sustainable food security in general, and rice production in particular, require the mobilization of political support to reform existing policies and encourage cooperation and coordination between the central government and different states. Food security also depends on the management and conservation of the natural resource base in a manner that will ensure the continued supply of rice for future generations. In this context, sustainable determinants and nonsustainable indicators have been identified for different agroecological zones. To bridge technology transfer gaps, different methods are suggested for achieving sustainability.

Current constraints to rice production and consumption may be ameliorated by research and development in an international context. Decentralization of research and technology development based on the comparative advantages and needs of different countries may contribute to synergy and further progress for all.

Planning for sustainable food security should emphasize information availability, resource use efficiency and management, input policies, policy research, and technology development. The greatest challenge will be to reform policy processes themselves, which will have to focus more on participation and social mediation to counter the complexities and uncertainties in achieving sustainability of rice production.

Rice is the staple food for 65% of the population in India. The crop accounts for about 22% (42 million ha) of the total cropped area, which represents 34% of the area under food crops and 42% of the area under cereals (Table 1). India is the second largest rice-producing country in the world. An output of 82 million t during 1994-95 accounted for approximately 46% of cereal production and 43% of the total food grains. Likewise, rice is the largest calorie source among the food grains. With a per capita availability of 73.8 kg (Table 2), rice meets 31% of the total average calorie requirement (Table 3). It accounts for 30–50% of agricultural income.

Exports of rice steadily progressed from 400,000 t in the mid-1980s to a formidable 5.5 million t by 1995-96, worth Rs. 45.3 billion in foreign exchange (Figs. 1 and 2). Following the liberalization of international trade after the World Trade Agree-

**Table 1. Share of rice in cereals and total food grains in India (1994-95).**

| Crop | Area (million ha) | Production (million t) |
|---|---|---|
| Rice | 42.24 | 81.16 |
| | (34.19)[a] | (42.47)[a] |
| | (42.08)[b] | (45.86)[b] |
| Wheat | 25.64 | 65.47 |
| | (20.75)[a] | (34.26)[a] |
| | (25.54)[b] | (36.99)[b] |
| Coarse cereals | 32.25 | 30.35 |
| | (26.18)[a] | (15.88)[a] |
| | (32.13)[b] | (17.15)[b] |
| Total cereals | 100.38 | 176.98 |
| | (81.25)[a] | (92.61)[a] |
| Total pulses | 23.17 | 14.12 |
| | (18.75)[a] | (7.39)[a] |
| Total food grains | 123.55 | 191.10 |

[a] Indicates percentage to total food grains. [b] Indicates percentage to total cereals.

**Table 2. Per capita milled rice consumption (kg $yr^{-1}$) in selected Asian countries vis-à-vis the world, 1964-91.**

| Year | India | Japan | Myanmar | Asia | World |
|---|---|---|---|---|---|
| 1964-66 | 64.9 | 99.8 | 131.0 | 73.3 | 47.6 |
| 1969-71 | 64.7 | 85.9 | 148.4 | 75.7 | 49.8 |
| 1973-74 | 60.7 | 80.2 | 157.4 | 75.6 | 50.5 |
| 1979-81 | 64.2 | 69.1 | 173.1 | 79.1 | 53.4 |
| 1984-86 | 68.2 | 65.2 | 183.6 | 84.2 | 57.0 |
| 1989-91 | 73.8 | 61.3 | 192.7 | 85.1 | 58.0 |

Table 3. Rice calorie supply as a percentage of total calorie supply in different Asian countries.

| Year | India | Japan | Myanmar | Asia | World |
|---|---|---|---|---|---|
| 1962 | 35 | 46 | 70 | 37 | 21 |
| 1972 | 34 | 33 | 75 | 38 | 23 |
| 1982 | 33 | 27 | 74 | 37 | 23 |
| 1992 | 31 | 24 | 77 | 35 | 23 |

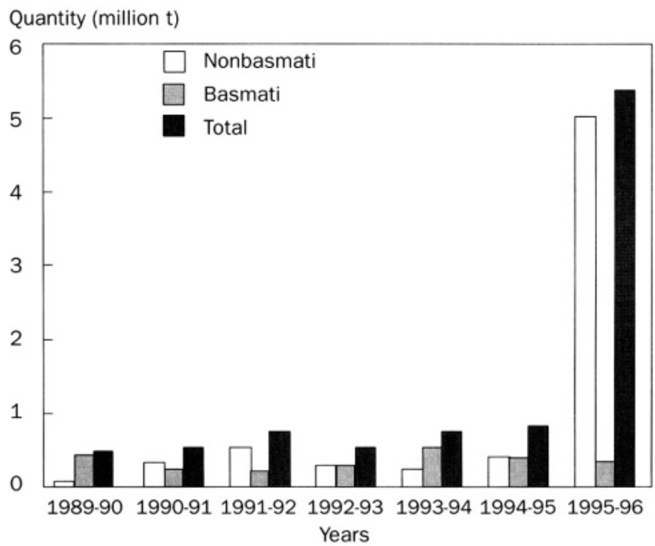



**Fig. 1.** Export trends (quantity) of basmati and nonbasmati rice from India.

ment, Indian rice has become highly competitive in the world marketplace and has been identified as one of the major commodities for export. Value-added products of rice now being developed (Table 4) are expected to provide further opportunities for earning foreign exchange. Because rice is India's most important source for meeting caloric and dietary protein needs as well as for generating employment and income, particularly for low-income groups in rural areas, the industry's growth and stability are vital for national food and nutrition security.

## Rice production: growth, current status, and future needs

Growth in rice production over the past 30 years has transformed chronically food-deficient India into a nation marked by surplus. More than 50 million t added to the total of the mid-1960s enabled India not only to do away with imports but to also have as much as 10 million t, valued at Rs. 30 billion, in buffer stocks. The increased

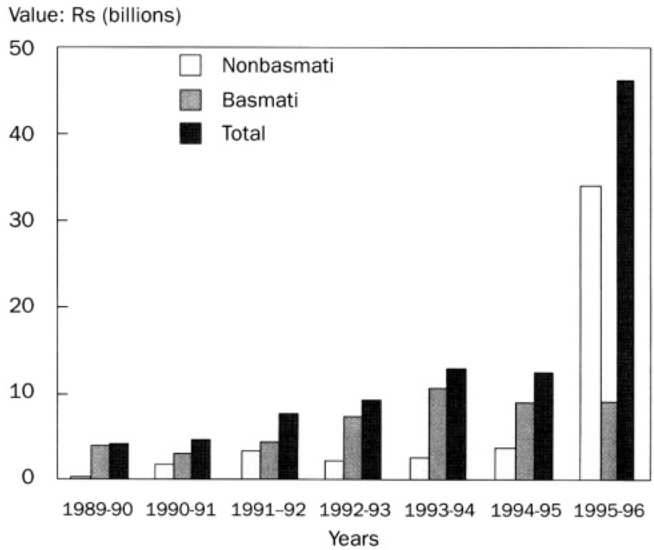



**Fig. 2.** Export trends (value) of basmati and nonbasmati rice from India.

**Table 4. Processed rice products.**

| Type | Examples |
|---|---|
| Easy cooking and instant rice | Canned rice, frozen rice, easy-to-cook brown rice, boil-in-bag rice |
| Roasted and puffed rice | Rice flakes, puffed rice, shredded rice, beaten rice |
| Canned convenience foods | Soups with rice, meat and rice dinner, casseroles (Shrimpereole), poultry and rice products |
| Rice flour-based crackers | Rice noodles, rice bread, rice-cake foods and crackers |
| Infant foods | First solid food |
| Fermented foods/drinks | Rice wines (sake, Japan; shaoshinchu, China) |

production during this period (Fig. 3) has mainly been due to improved technologies, such as high-yielding varieties, increased fertilizer and other input use, and adoption of improved crop and pest management practices. The average area in high-yielding varieties increased from 2.5% to 64.6% during this period (Fig. 4), while fertilizer (NPK) consumption increased from 10 to 120 kg ha$^{-1}$ (Fig. 5). Expansion of rice area from 35.47 to 42.24 million ha (Fig. 6), and coverage of area under irrigation, from 36.5% to 45.2%, contributed 8.3% and 15%, respectively, to the advances in production.

As in other crops, yield and growth patterns show a wide variation (Table 5). For instance, the average yields during 1994-95 were 1,208, 1,859, 2,550, and 3,383 kg ha$^{-1}$ in Madhya Pradesh, Uttar Pradesh, Andhra Pradesh, and Punjab, respectively. Statewise time series data aggregated into four major regions—southern, eastern,

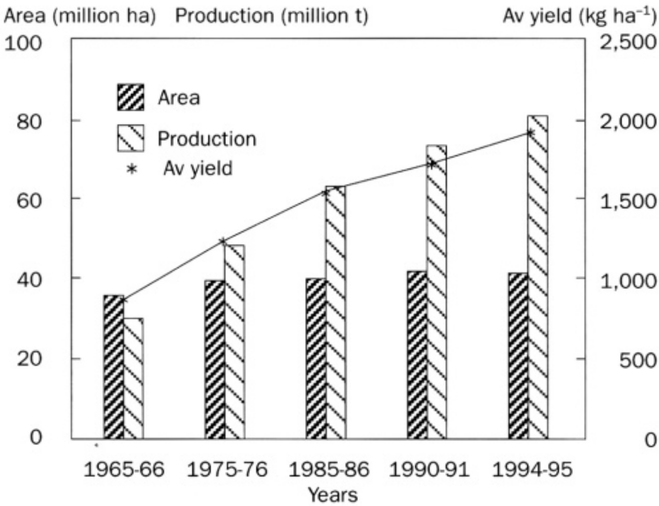



**Fig. 3.** Rice production trends in India.

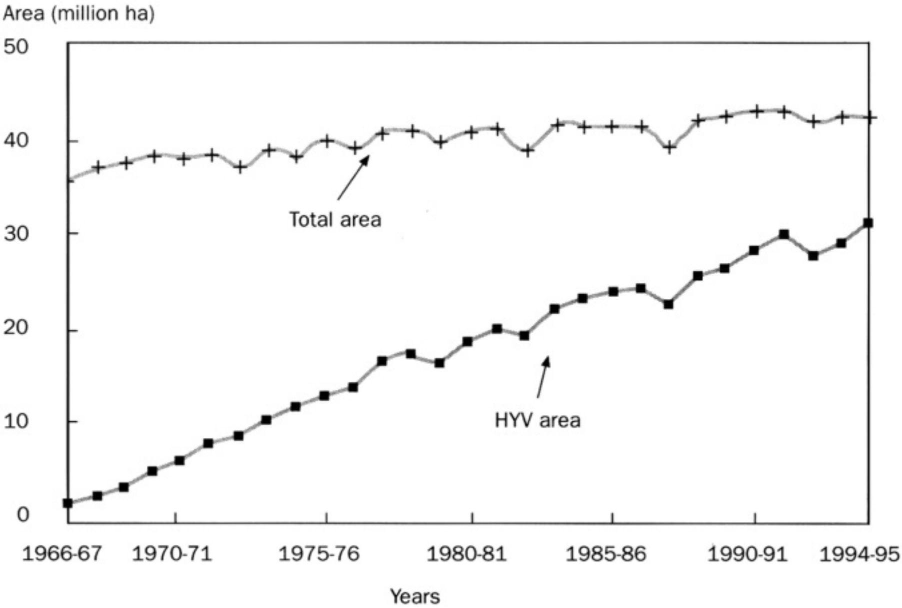



**Fig. 4.** Area under high-yielding varieties of rice in India (1966-67 to 1994-95).

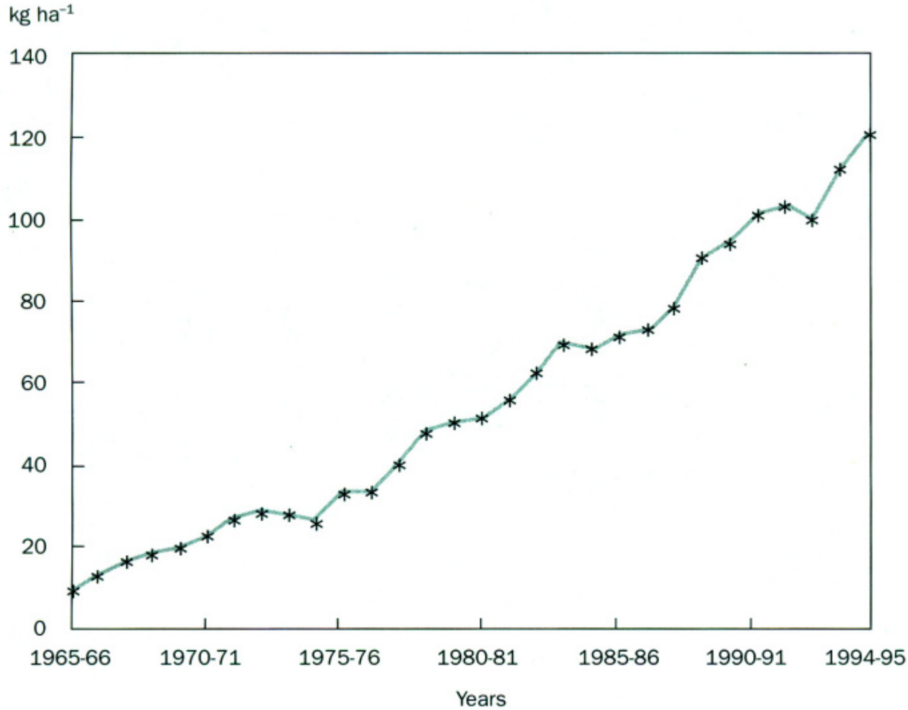



**Fig. 5.** Fertilizer consumption (estimated) for rice in India.

western, and northern—for growth trends in area, production, and yield (Table 6), clearly show that the northern states, including Haryana, Punjab, Western Uttar Pradesh, and Jammu and Kashmir, contributed the most to production, with an overall growth of 6.87%. The growth rate of yield declined from 6.5% in the decade of 1965-75 to 2.57% in the decade of 1985-95 in the western states, and remained more or less stagnant at around 2.51% in the south. It is encouraging to note that the eastern region, where yield was stagnant at a very low level for a long time, has realized high growth rates in production and productivity from 1985 to 1995. Overall growth rates for production and productivity in the whole of India were higher at 3.99% and 2.77%, respectively, during 1985-95 compared with earlier periods.

Globally, according to FAO statistics, rice production in 1994 was approximately 529 million t, 4 million t more than the output of previous years. Asia's rice production was estimated at 481.7 million t, representing an increase of 2.2 million t over the previous year. India's contribution, as indicated earlier, was 120 million t of paddy (82 million t of milled rice), or around 1 million t more than the previous year. At the present rate of population growth, India needs to add at least 2.5 million t of milled rice every year to sustain the current self-sufficiency. Despite an impressive growth rate in recent years, it may not be an easy task to achieve the targeted production of 95

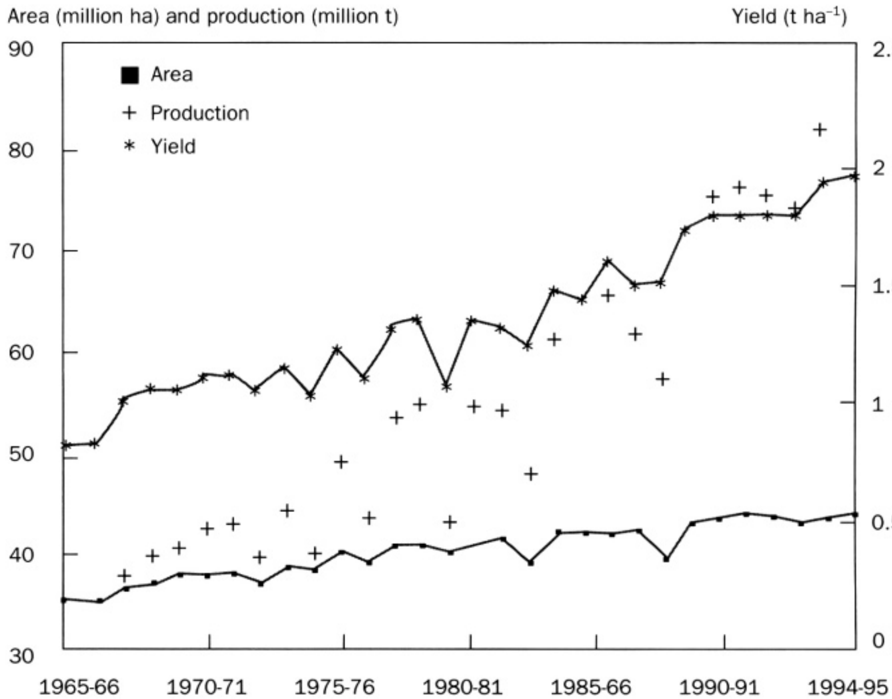



**Fig. 6.** Area, production, and yield of rice in India.

million t by 2000 and almost 135 million t by 2020. With no scope for growth in area, yield growth at not less than 3% per year is the only option for achieving future production targets.

## Yield gap and production constraints

Rice yields fluctuate greatly in time and space on account of the crop's cultivation under diverse weather and ecological and socioeconomic conditions. Of the 42 million ha of rice, 19 million ha (under 45%) are irrigated and the remaining 23 million ha are under fragile rainfed conditions, often affected by aberrations of monsoon. Rainfed ecologies predominate in eastern India and include lowlands (14 million ha), uplands (6.4 million ha), and flood-prone areas (3 million ha) (Fig. 7). Rice productivity in the irrigated ecosystem ranges from 2.3 t $ha^{-1}$ in Karnataka to 3.5 t $ha^{-1}$ in Punjab. Rainfed ecologies of shallow lowland, flood-prone, and upland areas register average productivities of 1.6, 1.0, and 0.5 t $ha^{-1}$, respectively (Fig. 8). The gap in yield levels between the national demonstration average and the national average is 0.6 t $ha^{-1}$ in irrigated areas and 1.5 t $ha^{-1}$ in rainfed areas (Fig. 9). Constraints responsible

**Table 5. Rice area, production, and productivity (1994-95).**

| State | Area (000 ha) | Production (000 t) | Productivity (kg $ha^{-1}$) |
|---|---|---|---|
| Andhra Pradesh | 3,640 | 9,234 | 2,550 |
| Arunachal Pradesh | 120 | 109 | 1,180 |
| Assam | 2,451 | 3,309 | 1,331 |
| Bihar | 4,727 | 6,168 | 1,284 |
| Goa | 55 | 138 | 2,519 |
| Gujarat | 611 | 942 | 1,403 |
| Haryana | 795 | 2,227 | 2,732 |
| Himachal Pradesh | 83 | 112 | 1,238 |
| Jammu & Kashmir | 273 | 507 | 1,863 |
| Karnataka | 1,308 | 3,193 | 2,283 |
| Kerala | 501 | 969 | 1,878 |
| Madhya Pradesh | 5,353 | 5,998 | 1,208 |
| Maharashtra | 1,538 | 2,898 | 1,608 |
| Manipur | 161 | 345 | 2,154 |
| Meghayala | 103 | 119 | 1,131 |
| Mizoram | 67 | 100 | 1,878 |
| Nagaland | 136 | 174 | 1,343 |
| Orissa | 4,456 | 6,538 | 1,452 |
| Punjab | 2,277 | 7,708 | 3,383 |
| Rajasthan | 155 | 172 | 1,016 |
| Sikkim | 16 | 21 | 1,286 |
| Tamil Nadu | 2,337 | 7,686 | 2,841 |
| Tripura | 258 | 493 | 1,813 |
| Uttar Pradesh | 5,582 | 10,114 | 1,859 |
| West Bengal | 5,774 | 12,464 | 2,011 |
| All India | 42,777 | 81,738 | 1,879 |

**Table 6. Zonal compound growth rates (%) of area, production, and yield of rice in India in important states.**

| Factor | Period | | | |
|---|---|---|---|---|
| | 1965-66 to 1974-75 | 1975-76 to 1984-85 | 1985-86 to 1994-95 | 1965-66 to 199495 |
| Area | | | | |
| East | 1.02 | –0.31 | 0.33 | 0.43 |
| North | 1.31 | 3.41 | 1.39 | 2.15 |
| South | 0.16 | –0.57 | 0.83 | –0.14 |
| West | 0.51 | 0.85 | 0.89 | 0.72 |
| All India | 0.77 | 0.36 | 0.61 | 0.59 |
| Production | | | | |
| East | 2.36 | 0.52 | 3.16 | 2.32 |
| North | 7.85 | 7.79 | 4.00 | 6.87 |
| South | 2.99 | 1.69 | 3.36 | 2.14 |
| West | 4.19 | 1.28 | 3.49 | 2.99 |
| All India | 3.31 | 2.22 | 3.39 | 3.07 |
| Yield | | | | |
| East | 1.32 | 0.83 | 2.82 | 1.88 |
| North | 6.46 | 4.24 | 2.57 | 4.62 |
| South | 2.82 | 2.28 | 2.51 | 2.27 |
| West | 3.67 | 0.43 | 2.58 | 2.25 |
| All India | 2.52 | 1.86 | 2.77 | 2.47 |

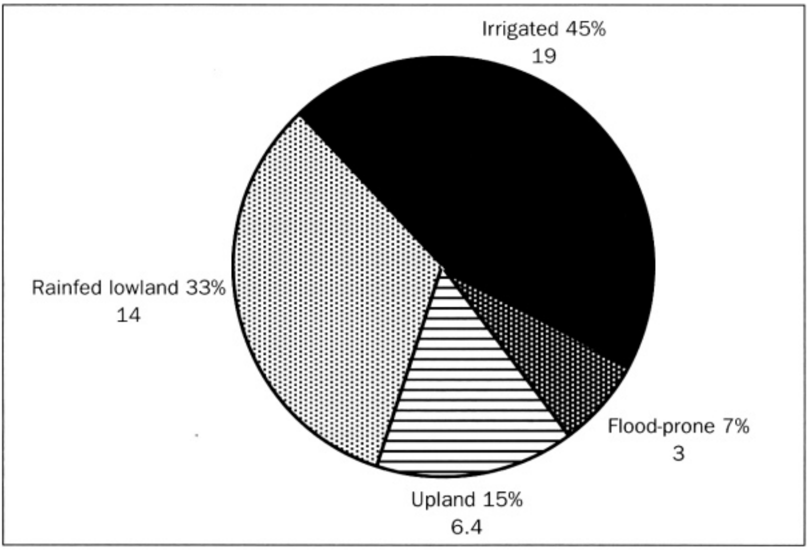


**Fig. 7.** Rice area (million ha) by ecosystem in India.

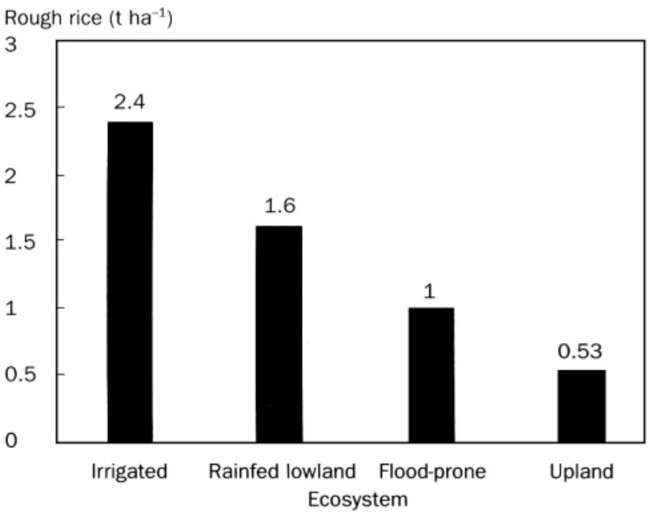


**Fig. 8.** Rice yield by ecosystem in India.

for lowering yield are principally technical and socioeconomic. Major constraints identified in each rice ecosystem are as follows:

A. Irrigated rice

1. Erratic monsoons, which delay water availability from canals and hence delay planting.

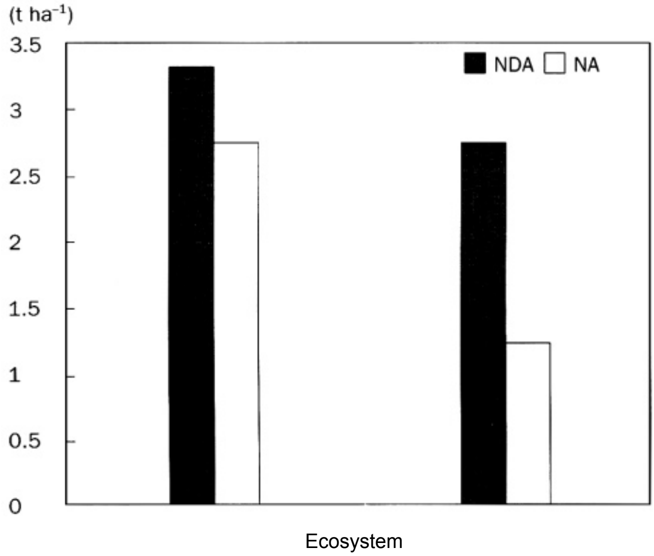



**Fig. 9.** Rice yield potential and realization. NDA = national demonstration average, NA = national average.

2. Degradation of soil caused by rising groundwater tables and salinity levels.
3. N-driven depletion of soil fertility and related problems caused by excessive soil mining.
4. Changes in physicochemical soil properties and ensuing reduced nutrient-supplying capacity.
5. New and emerging problems of multinutrient deficiencies.
6. Severe incidence of pests and diseases.

B. Rainfed upland rice
1. Erratic and often inadequate rainfall and lack of facilities for essential irrigation.
2. Fragile and impoverished soils because of erosion.
3. Soil acidity leading to saturation, phosphate fixation, Al toxicity, Mn toxicity, etc.
4. Iron chlorosis in calcareous/alkaline soils.
5. Poor land preparation and inadequate stand establishment because of high tiller mortality.
6. Severe weed infestation.
7. Continued use of traditional varieties.
8. Inadequate use of fertilizers, herbicides, etc.
9. Severe incidence of blast, brown spot, and termites.

C. Rainfed shallow lowland and semi-flood-prone rice

1. Impeded drainage and waterlogging because of growing urbanization.
2. Accumulation of toxic decomposition products in poorly drained soils and soil reduction, thus aggravating the problems of iron toxicity or sulfide injury.
3. Flash floods causing inundation and intermittent droughts, which affect crop growth at various stages of development.
4. Delayed monsoon, often resulting in delayed planting.
5. Agro-energy crisis and inadequate mechanization, leading to delayed sowing, planting, and harvesting.
6. Poor tillering coupled with high seedling/tiller mortality.
7. Excessive weed growth under broadcast conditions coupled with inadequate weeding.
8. Inadequate and imbalanced use of fertilizers and other agro-inputs.
9. New and emerging problems of multinutrient deficiencies such as P, Zn, and sulfur.
10. Continued use of traditional low-input and low-yielding varieties.
11. Nonavailability of short-duration *ahu* (summer) varieties, leading to delayed planting of *sali* (winter) rice.
12. Inadequate supply of quality seed.
13. Incidence of bacterial blight, sheath blight, rice tungro virus, blast, bacterial leaf streak, sheath rot, cutworms, leaffolders, stem borers, etc.

D. Flood-prone rice

1. Lack of appropriate HYVs possessing tolerance of drought in the seedling phase and of submergence with a rising water level later, as well as resistance to stem borers and sheath blight.

## Technologies available

### Varietal development

More than 500 high-yielding varieties for irrigated and rainfed ecologies have been released for general cultivation in India. These offer a wide choice of grain quality, resistance to various insect pests and diseases, and tolerance of abiotic stresses such as soil problems, drought, submergence, temperature extremes, and micronutrient deficiencies (Table 7). Recent developments in heterosis breeding, leading to the release of a dozen rice hybrids by the public and private sectors, have increased possibilities to raise the yield ceiling in high-productivity areas by 1–1.5 t over that of the predominant current varieties (Table 8).

### Soil and crop management

To sustain soil health and productivity at higher levels, a number of location-specific crop management practices have been developed. Table 9 lists these practices developed for different ecosystems.

### Integrated pest management

Pest and disease problems have become increasingly complex and difficult to manage because of newly emerging pest/biotype/pathotype variations and pesticide resistance. Integrated pest management technologies using resistant/tolerant varieties, cultural methods, natural biocontrol agents (either by conservation or inundated release [1]), and the need-based use of pesticides developed for areas with different pest and crop management profiles will have to be popularized in all pest-endemic areas (Table 10).

## Potential for future growth and opportunities

Despite impressive progress in increasing food production in general and rice production in particular, crop productivity and input use efficiency in India are among the lowest in the world. This is certainly not because the nation lacks improved technology, but because there are many other missing links. A review of the results of the national demonstrations conducted in farmers' fields in different parts of the country has shown that productivity of most crops, both in rainfed and irrigated areas, could

**Table 7. Popular high-yielding varieties for different ecologies.**

| Ecology | Varietal name |
|---|---|
| *Rainfed upland ecosystem* | |
| Andhra Pradesh | Prassanna, Rabi, Rudramma |
| Bihar | Birsadham 101, Birsadham 102, Birsadham 103, Birsadham 104, Tulsi |
| Gujarat | Gaur 3, GRS |
| Madhya Pradesh | Poorva, Jr 75, Kalinga III, Tulasi, Aditya, Annada, Tuljapur-1, Prabhavati |
| Orissa | Kalinga III, Pathara, Annada, Heera, Sneha, Kalyani II, Ghanteswari, Annapurna, Khandaglri, Niliagir |
| Tamil Nadu | TKM 9, Pramakudi-1, MDU-1, ADD-17 |
| Uttar Pradesh | Narendra, Narendra 80, Narendra 97, Narendra 118, Govind |
| West Bengal | Keron, Kalinga III |
| Assam | Kalinga III, Heera, Annada, Luit, Kapolee |
| *Rainfed shallow lowland* | |
| Andhra Pradesh | Swarna, Sona Mahsuri, Samba Mahsuri, Pinakhini, Thikana, Krishnaveni, Chandana Simhapuri, Phalguna |
| Assam | Bahadur, Ranjit, Sushal, Moniram, Manoharsali, Pankaj, Salivahana, Lakshmi |
| Bihar | Jayashree, Radha, Kanak, Sujata |
| Karnataka | Intan, Abilash, Mandya, Vijaya, IET 7191 |

Table continued

[1] Conservation release refers to the selective and controlled release of a biocontrol agent where it multiplies under field conditions. Inundated release is when the biocontrol agent is multiplied and released in large numbers.

**Table 7 continued.**

| Ecology | Varietal name |
|---|---|
| Kerala | Neeraja, Nila, Kayamkulam-1 |
| Madhya Pradesh | Ruchi, Sufri 17, Kranti, IR 36 |
| Orissa | Samaleie, Utkalaprabha, Gayatri, Tulshi, CR 1014, Padmini, Seema, Moti, Bhanja, Samanta, Bhuban, Manika, Urvasi, CR 1002, Dharitri |
| Pondicherry | Puduvai Ponni-1 |
| Tamil Nadu | Savithri, Ponni, Paiyur-1, CO 36, CO 45 |
| West Bengal | Swarnadhan, Jagannath, CR 1002, Radha |
| Maharashtra | Darana, Ratnagiri-2 |
| *Rainfed semi-flood-prone* | |
| Andhra Pradesh | Bradava Mahsuri |
| Bihar | Panidhan 1, Panidhan II, Janaki |
| Orissa | Utkal Prabha, Panidhan |
| Uttar Pradesh | Madhukar, Jalmagna, Jallahir, Jainidhi |
| West Bengal | Biraj, Mandira, Jogen, Savita, Matangini, Dinesh, Amulya, Nalini |
| *Rainfed postflood situation* | Heera, Luit, Kapil, Pusa 2-21, Tulasi, Kalinga III, Kalyani II, Vanaprabha, Lachit |
| *Hill region varieties* | |
| Jammu & Kashmir | Giza 14, PC 19, K 84, K 78-13, K-39 |
| Himachal Pradesh | Himdhan, Himalaya 741, Himalaya 799, Nagarjun, RP-732 |
| Uttar Pradesh | VL Dhan 39, VL Dhan 163, VL Dhan 221, Pant Dhan 11 |
| *Basmati rice* | Pusa Basmati-1, Kasturi, Haryana Basmati-1 |
| *Irrigated mid-early duration* | |
| Andhra Pradesh | Tella Hamsa, Puskala, Satya, Rudramma, Varsha, Dhanya Lakshimi, IR 64, Vikas, Rasi |
| Assam | Lachit, Chellari |
| Bihar | Prahlad, Narsing |
| Gujarat | Guar 11, GR 4 |
| Karnataka | Mangala, Pushpa, Maheveer |
| Kerala | Jyothi, Pvizham, Onam, Kairali, Aathira |
| Madhya Pradesh | Madhuri, Kranti |
| Maharashtra | Prabhavait, Ratnagiri-1, Karjat-1, ACK-5, Ambic, Sindewahi-1, Pavana, Kundhika, Terna, SYEER-1, Saholi-6 |
| Orissa | Ratna, Daya, Sarna, Neela, Tara, Annanga, Sravani, Lalat |
| Pondicherry | Bharthidasan, Jawahar |
| Punjab | PR 103 |
| Tamil Nadu | TKM 9, CO 41, ADT 36, ADU-1, IR50, ASD-16, ADT 37, ADT 39, ASD-17, MDU 4, IR64, JJ 92 |
| Tripura | TRC Borodhan-1 |
| Uttar Pradesh | Saket-4, Govind, Pant Dhan-4, Manohar Pant Dhan-6, Pusa 169 |
| West Bengal | Lakshimi, Khittsh, Kunti, Panke |
| *Irrigated medium duration* | |
| Andhra Pradesh | Vamshi, Divya, Vikramarya, Sonasali, Prabhat, Suraksha, Sasyasree, Jaya |
| Assam | Lakshmi, Madhu, Rangdoi |
| Bihar | Sita Rajendradhan 201, Kamini, NDR 359 |
| Gujarat | GR 101, GR 102, Ambica |

Table continued

**Table 7 continued.**

| Ecology | Varietal name |
|---|---|
| Haryana | HKK 120, HKR 126, Haryana Basmati-1, Pusa Basmati 1, Pusa 44-33, Ajaya |
| Karnataka | Pragathi, Prakesh, Mandyavaini, Avinash, Jayanthi, Sabari, Bhadra |
| Kerala | Rasmi, Swarna Prahba, Kanakan, Jayanthi, Sabari. Bhadra |
| Madhya Pradesh | Patel 85, Ruchi, Safri 17 |
| Maharashtra | Indryani, SKL 47-8, Palghar-1, Sindewahi, Kundalika |
| Orissa | Jajati, Udaya, Gauri, Kshira, Bhuban, NDR 359, Punithavathi, Ajaya |
| Pondicherry | Punithavathi, Ajaya |
| Punjab | PR 106, PR 108, PR 109, PR 110, Basmati 385, Pusa 44-33, Ajaya |
| Rajashtan | Chambal, BK 190, BK 79 |
| Tamil Nadu | CO 43, CO 44, ADU-2, Thirupathisaram-1, TPS-2, ADT 38, MDU-3, TKM 10 |
| Uttar Pradesh | Sarjoo 52, Pant Dhan 10, NDR 359 |
| West Bengal | Kunit, Munal |
| *Pest - and disease - resistant varieties* | |
| Gall midge-resistant varieties | |
| Biotype 1 | Phalguna, Vibhava, Surekha, Suraksha, Kavya, Errammalelu, Ruchi, Shaktiman, Pothana, Divya, Shakti, Lalat |
| Biotype 2 | Samalei, Sathi, Gauri, Phalguna |
| Biotype 3 | Rajendradhan 202 |
| Biotype 4 | Suraksha, Abhaya, IET 10831 |
| Bacterial leaf blight -resistant varieties | Ajaya, PR 110 |
| Rice tungro virus-resistant varieties | Vikramarya, IET 9994 |
| Brown planthopper-resistant varieties | Nagarjuna, Sonasali, Chandana, Krishnaveni, Chaitanya, Ramya, Kanakam, Aruna, Makom, Kartika, Vijram, Nandi |
| Whitebacked planthopper-resistant varieties | HKR 120 |

**Table 8. Public-bred hybrids released. About six private-sector hybrids are being marketed.**

| Hybrid | Parentage | Duration (d) | Area of adaptability |
|---|---|---|---|
| APRH-1 | IR58025A/Varjram | 130–135 | Telanagana and Rayalaseema regions and Andhra Pradesh |
| APRH-2 | IR62829A/MTU9992 | 120–125 | Telanagana and Rayalaseema regions and Andhra Pradesh |
| DRRH-1 | IR58025A/IR40750 | 125–130 | Telanagana and Rayalaseema regions and Andhra Pradesh |
| KRH-1 | IR58025A/IR9761 | 120–125 | Irrigated areas of Karnataka |
| MGR-1 | IR62829A/IR10198 | 110–115 | For May/June planting in Tamil Nadu |
| CNRH-3 | IR62829A/Ajaya | 125–130 | For boro season cultivation in West Bengal |

**Table 9. Crop management practices developed for the irrigated ecosystem.**

- Grow prekharif green manure/grain legumes (green gram) wherever plantings are taken up in August and incorporate before planting.
- Wherever irrigation water is available, plant early in July.
- Exploit nonmonetary inputs in rice cultivation by close planting (50–55 hills $m^{-2}$) and shallow planting for vigorous tillering.
- In tankfed areas and under delayed-monsoon kharif seasons, the problem of overgrown seedlings is often encountered. To obtain normal yields with aged seedlings, plant 4–5 seedlings $hill^{-1}$ (to compensate for loss in tillering ability) and apply 50% extra nitrogenous fertilizer as basal dose.
- Maintain a balanced use of fertilizer by ensuring applicatlon of NPK in the ratio of 4:2:1. Apply N (80–110 kg $ha^{-1}$) in 3 equal splits (at basal, tillering, and panicle initiation stage). In light soils (sandy soils), more splits are recommended. Apply all P (60 kg $P_2O_2$) and K (40 kg $K_2O$) as basal.
- Apply Zn at 40 kg $ZnSO_4$ for every 3 crop seasons for normal soils: double the initial dose for saline-alkaline soils. For midseason correction, spray 0.2% $ZnSO_4$ three times at weekly intervals starting from the third week of planting.
- Use chemical weedicides such as butachlor + safener or anllophos + 2,4-D Na wherever labor is scarce.

be increased considerably by using the currently available improved technology package. What is required is the identification of potential areas in both irrigated and rainfed ecologies that can benefit from an intensive focus on meeting their particular developmental and technological needs. The following opportunities suggest themselves:

- Vast low- and medium-productivity areas under irrigation.
- Vast monocropped areas with rich groundwater/surface water in high rainfall regions with potential for raising a second (*rabi*) crop.
- Relatively favorable areas for intensive farming in otherwise harsh rainfed ecologies.
- Tactical crop planning to avoid or overcome crop losses caused by flash floods.

Wide inter- and intradistrict differences in yield of irrigated rice suggest that one potential may lie in increasing production through better diffusion of technology or developmental remedies. Limited surveys of such areas in some states suggest that low or medium productivity is often due to inadequate or imbalanced fertilizer use, degraded soils, impeded drainage, unscientific irrigation management, and severe recurrent incidences of pests and diseases. District data, collected from states such as Uttar Pradesh and Andhra Pradesh, can be analyzed to identify and correct key constraints to production.

A close review of rice area and productivity trends during the kharif and rabi seasons reveals that the area of rabi rice is shrinking, although the average productivity of rabi rice is quite high, more than 3.27 million t $ha^{-1}$ in the south. In the northeastern states, rabi rice averaged 2.71 t $ha^{-1}$ versus 1.66 t $ha^{-1}$ during the kharif season in 1991-92. Andhra Pradesh, Tamil Nadu, Karnataka, West Bengal, Orissa, Bihar, and Assam have a greater potential for increasing rabi rice area through the combined use

**Table 10. Insect pest and disease management practices.**

- Cultivate high-yielding disease/pest-resistant/tolerant/multiple-resistant varieties in endemic areas.
- Treat seed with 0.1% Beam 75 WP/Bavistin 50 WP for blast control.
- Use a nursery treatment with effective insecticides to obtain pest-free and healthy seedlings.
- Adopt seedling root dip in 0.2% chlorpyriphos emulsion for 12 h prior to transplanting to protect the crop up to 25 d against insect pests, which is cost-effective and safe for natural enemies.
- Adopt cultural practices such as timely planting, good crop sanitation, destruction of stubble and excess nurseries, optimum plant spacing, and the avoidance of an excess use of nitrogenous fertilizers.
- Use only effective insecticides at recommended doses on a need basis taking into consideration economic thresholds and natural enemies as revealed by regular surveillance; recommended insecticides include carbofuran, phorate, quinalphos, and cartap as granules, and monocrotophos, chlorpyriphos, quinalphos, phasolone, endosulfan, carbaryl, phosphamidon, and ethfenprox as sprays. In general, sprays are good at 0.35–0.50 kg a.i. $ha^{-1}$ and granules at 0.75–1.00 kg a.i. $ha^{-1}$ against the rice insect pest complex.
- Use effective fungicides for blast such as Bavistin 50 WP, Topsin 560 EC, Kitazin 49 EC, and Beam 75 WP all at 0.1% dosage; for brown spot, Dithane M-45 WP (0.3%); for sheath blight, hexaconazole 5 EC (2 g $L^{-1}$).

*For rainfed upland rice*

- Short-duration, drought-tolerant varieties suited for direct seeding.
- Line sowing, optimum plant stand, economical weed management.
- Deep summer plowing.
- Stale seedbed.
- Moderate fertilizers, apply NPK at 50:25:25 kg $ha^{-1}$.
- Seed treatment with carbendaizim/soil application of BHC dust in termite-endemic areas.
- Need-based chemical control against blast, stem borer, gundhi bug.

*For rainfed lowland rice*

- Approved high-yielding varieties with photosensitivity.
- Transplanting wherever water depth does not exceed 30 cm.
- Direct seedling in medium and flood-prone conditions.
- High stand establishment, line sowing with high seed rate/closer planting.
- Apply NPK at 60:20:20 kg $ha^{-1}$.
- Rectify Zn and S deficiency. Weed control by herbicides wherever economical.
- Seed treatment with carbendazim.
- Need-based chemical control of insect pests and diseases.

of surface water and groundwater resources. In Bihar, Assam, and Orissa, there is scope to bring as many as 3 million ha into rabi rice production by taking full advantage of yearly recharged aquifers.

The available data on groundwater potential in Andhra Pradesh show that the groundwater balance available for development is almost 2.7 million hectare meters. The canal command districts of the coastal areas as well as Rayalaseema and Telangana are the richest sources of groundwater. The present use of groundwater is about 32% in Telangana, 33% in Rayalaseema, and 15% in the coastal districts of Andhra Pradesh. Exploration costs in command areas are likely to be less. If a policy decision is made on groundwater development in command areas, about 0.5–1.0 million ha of additional area in states such as Andhra Pradesh, Tamil Nadu, West Bengal, Orissa, Bihar, and Assam could possibly be brought under rabi/boro cultivation, which is the most productive season for rice.

Developmental efforts are likely to be productive for exploring groundwater potential in high-rainfall areas of Kerala, coastal Karnataka, Assam, Bihar, Meghalaya, and Orissa. The use of groundwater in these areas could facilitate timely sowing and early establishment of the rice crop, especially during the years of delayed onset of the southwest monsoon. Desilting available tanks and installing shallow tube wells could go a long way toward helping the timely establishment of the crop at a low cost.

The provision of drainage facilities in command areas in general, and in coastal regions in particular, is a high priority, which when done in a phased manner could greatly help resource conservation and the sustainability of rice production. The rainfed lowlands of eastern India constitute a major ecosystem, where impeded drainage is the most serious constraint to rice production. The recent experience of Krishna District in Andhra Pradesh, where a major attempt to overcome this problem resulted in increased productivity, can be a good example for many parts of Orissa, West Bengal, Bihar, Assam, eastern Madhya Pradesh, and the rice-growing states of the Konkan coast.

It would be a mistake to regard the entire rainfed ecology as environmentally handicapped and less productive. The constraints of water regimes vary in severity. Intelligent management lies in choosing a technology package suitable to different areas and transferring it to the farmers. In the lowlands, for instance, the emphasis should be on relatively favorable shallow-water (not exceeding 40 cm) areas. Similarly, under the upland ecology, areas with relatively more rain days and even distribution of rainfall should be chosen for intensive farming. In states like Assam, where floods are a recurrent problem, totally flood-free (30%) areas should be identified for intensive farming, taking advantage of high rainfall and even distribution. There is likewise ample scope for tactical crop planning in flood-ravaged areas. Developing appropriate varietal technology could allow a profitable use of pre- and postflood periods.

## Strategies for increasing rice production

Some of the major strategies for achieving the production target of 95 million t of rice by 2000 are: intensifying rice cultivation in the most favorable areas; consolidating yield gains under irrigated conditions; enhancing productivity under rainfed conditions; exploiting the potential of hybrid technology; promoting an adequate and balanced use of fertilizers, along with increased fertilizer and water use efficiency; identifying cost-effective and environmentally friendly production and protection technologies such as integrated nutrient management and integrated pest management; using rice-fallow-based cropping and farming systems; and narrowing the information gap between researchers and farmers.

If efforts are intensified in the most favorable areas for rice, production can be sharply increased with the current technology, provided support is given in the form of input supplies. Yield gains under irrigated conditions can be consolidated by diagnosing and correcting the problems associated with declining fertilizer use efficiency and unstable production growth. Similarly, to enhance productivity in rainfed areas, suitable high-yielding varieties and packages of crop production practices could be developed.

The Chinese have exploited hybrid vigor in rice as the best potential technology option for raising the yield threshold. Although hybrid technology has been successfully developed for crops such as maize, sorghum, cotton, and pearl millet over the past four decades, it was possible to commercialize rice hybrids in India only recently, following the release of six public-sector-bred and six private-sector-bred hybrids. The commercial exploitation of hybrid rice technology enabled China to gain an advantage of 15–20%in yield over the best varieties and to gain 20–25 million t of rice from 18 million ha. If 60–70% of India's irrigated rice area could be brought under hybrid cultivation, about 10–12 million t of rice could be added to the national average. Ongoing research to develop appropriate hybrids for favorable rainfed lowland conditions (7–8 million ha), if successful, could help increase yield appreciably.

The use of high-yielding hybrid rice and the popularization of HYVs would also increase demand for plant nutrients. Balanced fertilization in accordance with crop nutrient demand would ensure the targeted productivity, but the imbalanced use of fertilizer might lead to soil degradation and a subsequent decline in productivity. Generally, most fertilizer used on rice is confined to irrigated areas, which account for 45% of rice area, whereas rainfed uplands and lowlands receive very small quantities of fertilizer. If the HYVs developed for rainfed ecologies are to express their full potential, applying higher doses of fertilizer will be important.

Another area requiring attention is increasing the use efficiency of applied fertilizers, particularly nitrogen. Despite an impressive growth in nitrogen consumption over the years, efficiency of the nutrient in lowland rice remains very low because of losses through volatilization, runoff, and leaching. Techniques for minimizing nitrogen loss should be adopted more widely.

The assured availability of water is another important factor in rice production. The bulk of the area under rice in India depends on rainfall. Increased use efficiency will not only ensure rice production in the existing area but also facilitate bringing additional areas under irrigation.

High yields now being obtained cannot be sustained unless declining soil fertility caused by excessive nutrient mining and imbalanced fertilizer use is checked. Organic manures alone cannot be a solution because of their low nutrient content, slow release, and limited availability. Various limitations associated with production, storage, and use have also deterred the wide adoption of biofertilizers. Therefore, the best approach for sustaining soil fertility and crop productivity would be to integrate chemical fertilizer use with organic sources.

Sustainability should not be addressed on a crop-by-crop basis, but should be studied from a systems angle. There are many region-specific rice-based cropping systems. Because high-yielding hybrids and varieties need considerable nutrients for sustained productivity, a renewed approach to fertilizer management in rice-based cropping systems has become all the more relevant. A quantitative evaluation of the role of preceding crops and the residual effect of nutrients applied is thus important.

Integrated rice-based farming systems, such as rice with fish, poultry. dairy, and mushroom cultivation, are another viable concept for sustained productivity in today's agriculture. Various research results have indicated the advantage of such systems over conventional cropping systems. For instance, a conventional cropping system is vulnerable to a high degree of risk and uncertainty and provides only seasonal, irregular, and uncertain income and employment to farmers. A systems approach is the best way to reduce risks and uncertainties, to decrease the incidence of pests and diseases, and to reduce the time lag between investment and returns. Motivating farmers to opt for such types of production systems can help generate year-round income and employment besides facilitating a better use of resources.

## Regional strategies for increasing rice production

### Eastern India

Any major strategy for improving rice production in eastern India should start with a better understanding of its rice-growing environments and the identification of potential but hitherto underused areas for production. The rainfed shallow lowland (<30-cm depth) ecosystem is the minimum-risk ecology where, with the introduction of appropriate high-yielding varieties, minimum levels of input use, and the adoption of an improved package of management practices, it would be possible to increase productivity significantly.

Varieties are the major missing link in the most ecologically harsh environments of eastern India. The performance of currently available high-yielding varieties can be demonstrated along with recommended practices, through extensive compact-block demonstrations, to enlighten the extension personnel working in the area about the potential of the technology and to encourage rapid dissemination of varieties through seed exchange. Other strategies include:

- Introducing hybrid rice technology in the favorable shallow lowlands, after verifying the adaptability of hybrids for irrigated areas and the popularization of newly released hybrid CHNRH-3 in the boro season.
- Using a moderate level of inputs involving a balanced use of major and minor nutrients and correcting prevailing micronutrient deficiencies.
- Emphasizing stubble management, rainwater conservation, organic matter, and, particularly, recycling/green manuring wherever possible.
- Sowing early in direct-seeded areas and/or timely transplanting (by minimizing staggered planting) on a watershed basis, with due emphasis on establishing a minimum desired level of plant population.
- Popularizing small farm machinery such as power tillers, threshers, simple grain dryers, and grain storage equipment to cope with the problem of the increasing nonavailability of labor, to ensure timely farming operations and safe storage.

- Providing crop-saving irrigation through organized shallow tube wells, bamboo tube wells, and village tanks, etc., to cope with prolonged intermittent seasonal drought during the rice-growing season. Community irrigation as practiced in Assam, using a renewable energy source for water lifting, could be extended to other parts of eastern India (the Chattisgarh region of eastern Madhya Pradesh, northeastern and northwestern Bihar, many parts of Orissa, and West Bengal) to provide supplementary irrigation for rice during the critical phenological stages.
- Extending the boro crop to still unused areas in Bihar, Orissa, West Bengal, and Assam, with provision for tapping into groundwater.
- Emphasizing postrice cash crops of pulses/oilseeds such as lentil, linseed, toria groundnut, and sunflower, wherever possible making use of residual soil moisture.

## South India

Rice improvement in Kerala and Tamil Nadu will depend more on socioeconomic reorganization than on technology for the time being. Rice production must be encouraged through major socioeconomic corrections, policy support, and adequate farmer incentives to meet the extra costs of escalating labor wages and inputs. But certain technical strategies will also be important, such as:

- Exploiting groundwater potential thorough shallow tube wells in the Onattukarai tract and in the Pallial lands of north Kerala to help early establishment of the dry-sown crop in April–May so as to be prepared for the monsoon starting in June. This would improve productivity considerably during the *viruppu* or first crop season. This applies as well to the whole of the Konkan coast and parts of Tamil Nadu.
- Organizing compact-block frontline demonstrations to show the potential of a combination of a package of technologies and appropriate varieties that tolerate specific abiotic stresses in command areas such as salinity, zinc deficiency, and phosphorus deficiency and specific pest and disease problems such as rice tungro virus and gall midge.
- Establishing a tungro virus disease management campaign through organized demonstrations, using resistant varieties and cultural practices in the endemic areas of Chengelput, North Arcot and South Arcot districts of Tamil Nadu, and Nellore District of Andhra Pradesh, and a gall midge management campaign in Srikakulam and Vizianagaram districts of Andhra Pradesh.
- Correcting multinutrient deficiencies arising from phosphorus, potassium, zinc, and sulfur responses and following a balanced nutrient use in the medium- and low-productivity areas of Andhra Pradesh, Tamil Nadu, and Karnataka, with emphasis on green manuring, organic recycling, and stubble management.
- Increasing the area under heterotic hybrids such as APRH 2 in Andhra Pradesh, KRH 1 and KRH 4 in Karnataka, MGR 1 in Tamil Nadu, and DRRH-1 all over the south.

### North and northwest India

Medium-duration varieties with good grain quality and resistance to bacterial leaf blight should be grown in Punjab and whitebacked planthopper–resistant varieties in Haryana. Pusa-44 with desirable qualities and amenability for combine harvesting is highly preferable. High-yielding basmati varieties such as Pusa Basmati-1 should replace low-yielding ones in the entire traditional basmati area.

Rice hybrids of medium duration and tolerant of pests developed by the public and private sectors should receive intensive on-farm testing for their adaptability and subsequent spread. A seed production program for the identified hybrids should be established immediately. Effective management of yellow stem borer, leaffolder, bacterial leaf blight, and blast should be implemented with appropriate cultural methods and need-based pesticide use.

## Food security

Food security can be defined as the physical and economic access to food for all sections of a society at all times (Swaminathan 1993). Food security issues related to distribution and delivery of rice to consumers are as important as planning production. Sustaining self-sufficiency in rice production and maintaining incentive prices are important to avoid spending foreign exchange on food imports. Because sustainability concurrently emphasizes physical accessibility and economic affordability of consumers, we need to understand current price elasticities, support prices, and distribution and delivery systems in relation to planning rice production. India needs a cogent analysis of long-term production potentials and consumer needs with special reference to policy planning.

### Per capita availability

The net per capita availability of food grains in India has increased from 170.7 to 188.3 kg $yr^{-1}$ from 1989 to 1995, amounting to a 10.3% increase. The corresponding increases in per capita availability of rice and wheat were about 17.4% and 8.9%, respectively (Table 11). Availability of coarse cereals, on the other hand, declined by 16.7%. The data thus indicate that food grain availability is still below the normative intake of 194.5 kg fixed by the National Institute of Nutrition, whereas rice availability (86 kg) matches the recommended intake. The requirements for food grains and rice have been projected at 225 and 95 million t, respectively, for 2000.

### Constraints to food accessibility

The principal flaws in food security lie in the distribution and delivery systems. Some policy measures suggested to improve these systems involve stressing clear objectives, emphasizing planning ahead, encouraging community participation and local initiatives, fostering greater transparency in functioning, evolving improved mechanisms for coordination, decentralizing and delegating, using effective economies in management, building incentives for realistic user demand, reducing gender biases, and improving personnel management.

**Table 11. Average net per capita availability of food grains.**

| Cereal/pulses | Average net per capita availability (kg yr$^{-1}$) | | Change (%) |
|---|---|---|---|
| | 5-yr period ending 1989 | 5-yr period ending 1995 | |
| Rice | 73.7 | 86.5 | 17.4 |
| Wheat | 55.1 | 60.0 | 8.9 |
| Coarse cereals | 27.6 | 23.0 | –16.7 |
| Pulses | 14.3 | 18.8 | 31.5 |
| Total food grains | 170.7 | 188.3 | 10.3 |

Source: Directorate of Economics and Statistics, March 1996.

## Pricing policy

The nation's main policy objective over the past two decades has been to ensure remunerative grower prices with a view to encouraging higher investment and production as well as safeguarding consumer interests by making supplies available at reasonable prices. This pricing policy seeks to develop a balanced and integrated price structure within the perspective of the overall needs of the economy. The rise in support prices announced for rice has been higher than for any other cereal crop during the past decade. This strategy has been pursued to encourage farmers to use modern technology and thus raise the output of rice to meet increasing demand. Table 12 shows the percentage increases in procurement or minimum support prices of rice, wheat, and coarse grains from 1989-90 to 1992-93.

The minimum support price plays a decisive role in ensuring a reasonable profit to growers for their produce, keeping pace with increasing rice production costs. Policymakers are concerned that reduced net returns would affect farmers' interest and discourage them from growing more food and hence reduce long-term sustainability. In this context, it may be necessary to increase the minimum support price, and the state should continue to support basic services such as irrigation, electricity, etc. Other factors that reduce risks for rice producers, such as subsidized inputs, should also be considered.

## Public distribution system (PDS)

The PDS is a program under which the government supplies some essential items of daily use, such as rice, wheat, levy sugar, and edible oils, to the public at controlled prices through outlets such as ration shops and fair-price shops. The aim is to ensure stability in the general living standards of the population. Of these items, rice, wheat, sugar, and kerosene are the most important, accounting for 86% of the total PDS sale. Rice alone accounts for about 27%. A breakdown of the rural and urban sectors shows that kerosene, sugar, and rice are the most important items sold through the PDS in the rural sector, whereas rice and sugar form the basis for the general impression that the PDS commodity composition is weighted in favor of items that are supposed to be consumed largely by the urban community (Tables 13, 14, and 15).

**Table 12. Procurement prices vs cost of production of cereals, with procurement price in Rs/q.**

| Crop | Procurement price | | | Production cost | | |
|---|---|---|---|---|---|---|
| | 1989-90 | 1992-93 | Increase (%) | 1989-90 | 1992-93 | Increase (%) |
| Rice | 185 | 270 | 46 | 181 | 273 | 47 |
| Wheat | 215 | 330 | 54 | 180 | 264 | 47 |
| Coarse grain | 165 | 240 | 46 | 185 | 275 | 49 |

Source: Directorate of Economics and Statistics, March 1996.

**Table 13. A profile of purchases from the public distribution system (PDS), all India.**

| Item | Share (%) of total rural PDS purchases | Share (%) of total urban PDS purchases | Share (%) of total rural + urban PDS purchases |
|---|---|---|---|
| Rice | 26.63 | 26.88 | 26.70 |
| Wheat | 7.89 | 15.08 | 10.08 |
| Bajra | 0.11 | 0.03 | 0.09 |
| Jowar | 0.34 | 0.12 | 0.27 |
| Other cereals | 0.54 | 0.21 | 0.44 |
| Pulses | 0.18 | 0.23 | 0.20 |
| Edible oils | 7.37 | 11.23 | 8.54 |
| Sugar | 40.35 | 22.26 | 34.84 |
| Coal | 0.09 | 0.81 | 0.31 |
| Kerosene | 11.79 | 20.77 | 14.89 |
| Standard cloth | 4.71 | 2.18 | 3.94 |
| Total | 100.00 | 100.00 | 100.00 |

**Table 14. Composition of commodity market dependent population for all India.**

| Commodity | Rural India | | | Urban India | | |
|---|---|---|---|---|---|---|
| | Market dependence (%) using only PDS[a] | Market dependence (%) using PDS and other sources | Market dependence (%) using only other sources | Market dependence (%) using only PDS | Market dependence (%) using PDS and other sources | Market dependence (%) using only other sources |
| Rice | 14.18 | 25.56 | 60.26 | 11.14 | 27.97 | 60.89 |
| Wheat | 26.49 | 4.81 | 68.70 | 29.48 | 7.21 | 63.31 |
| Bajra | 1.07 | 0.41 | 98.53 | 1.05 | 0.00 | 98.95 |
| Jowar | 4.39 | 4.40 | 91.21 | 0.89 | 1.13 | 97.98 |
| Other cereals | 2.97 | 3.03 | 94.00 | 3.44 | 1.32 | 95.24 |
| Pulses | 0.03 | 0.04 | 99.93 | 11.32 | 11.77 | 76.92 |
| Edible oils | 4.57 | 12.11 | 83.32 | 5.74 | 20.89 | 73.37 |
| Sugar | 36.08 | 31.86 | 32.06 | 29.19 | 46.44 | 24.37 |
| Coal | 6.36 | 1.69 | 91.92 | 10.85 | 0.57 | 88.58 |
| Kerosene | 44.09 | 6.91 | 49.00 | 26.20 | 8.24 | 35.55 |

[a]PDS = public distribution system.

**Table 15. Composition (%) of cereal consumption basket in India.**

| Year | Rice | Wheat | Coarse cereals |
|---|---|---|---|
| 1958-59 | 43.9 | 30.3 | 25.9 |
| 1959-60 | 45.5 | 32.2 | 22.3 |
| 1960-61 | 47.5 | 33.9 | 18.6 |
| 1961-62 | 49.3 | 32.9 | 17.9 |
| 1962-63 | 47.6 | 37.6 | 14.8 |
| 1964-65 | 43.6 | 42.6 | 13.8 |
| 1972-73 | 47.3 | 38.0 | 14.7 |
| 1973-74 | 46.8 | 41.6 | 11.7 |
| 1977-78 | 46.8 | 42.4 | 10.9 |
| 1983 | 48.3 | 43.8 | 8.0 |
| 1986-87 | 47.6 | 44.3 | 8.2 |
| 1987-88 | 47.5 | 42.7 | 9.9 |
| 1988-89 | 47.8 | 43.6 | 7.2 |
| 1989-90 | 49.1 | 43.8 | 6.9 |
| 1990-91 | 49.6 | 42.7 | 7.6 |
| 1991-92 | 49.7 | 43.2 | 7.1 |
| 1992-93 | 49.8 | 42.7 | 7.6 |
| 1993-94 | 50.1 | 43.2 | 6.7 |
| 1994-95 | 50.4 | 44.5 | 5.1 |

**Source:** Govardhan and Rao 1996.

The current practice of universal eligibility has to change if the PDS is to act as a viable safety net and catalyst for using natural as well as human resources. Some options available are targeting by indicators, mechanisms such as using inferior-quality grain in the PDS, and removing regulations that compel the regular use of ration cards.

Leakages are a major problem in the PDS. Some evidence indicates that, at the state level, leakages of rice as a proportion of total distribution increase with the rural share and decrease with the relative size of the state's program. Prices appear to have a very weak influence, if any; research on large samples is necessary to further explore this relationship. Strengthening the administrative mechanism may help check leakages, but it is doubtful whether this will suffice. Using inferior qualities of grain will also help curb the incentive to divert. Over the long term, greater thought has to be given to restructuring the PDS, perhaps along the lines of a modified food stamp scheme whereby consumers can procure subsidized food by presenting entitlement stamps at any store. The level of subsidy required to run the subsidized food distribution program has reached alarming proportions, especially in view of India's difficult fiscal situation. What is worrisome is the extent of leakages to the free market (one-third) together with the weakness in targeting (40% to the poor). Apparently, only about a fourth of this subsidy actually reaches poor people.

The Food Corporation of India (FCI) at present procures about 11–12% of the net production of food grains in the country, or approximately 36 million t of buffer stock. The handling and function of buffer stock has become increasingly inefficient and costly. Increasing FCI inefficiency, as reflected in the substantial escalation in its handling, storage, and administrative costs, is one important reason behind the large increase in the subsidy. Of late, central government pricing decisions whereby price increases to farmers have not been completely passed on to consumers have also become important. Steps to curb FCI costs by recourse to increased private-sector participation are necessary. Also required is a review of the buffer stock policy in view of the considerable storage costs involved. The broad conclusion is that leakages into the free market are a serious problem, as is the weak targeting of the program.

### Infrastructural issues

Appropriate infrastructural support is essential for efficient marketing and distribution, and for promoting food security on a sustainable basis. The major issues in this respect are the following:

1. Provision of an adequate transport infrastructure, such as rural linking roads and transport equipment.
2. Creation of adequate market centers and farm service centers.
3. A need for market intelligence communicated through the mass media.
4. A need to create storage and processing facilities.

### Institutional issues

Several institutional issues are important:

- The lack of availability of credit for producers, particularly to finance working capital. Better credit arrangements could improve the withholding power of small farmers and others with marketable products.
- The role of private trader and farmer groups. Private traders, like moneylenders, play an important role in rural areas in food distribution and delivery, and it would be unrealistic to think that these roles can be eliminated. Measures might, however, be introduced to make lending more competitive. Such competition could come first and foremost from farmer groups and associations.
- Commodity-based targeting could dismantle the FCI and encourage bids for food grain delivery, and replace the PDS with food stamps.

### Women and household food security

Women's contribution to food production is of paramount importance to sustainability. Women are often the main food producers, income earners, and guardians of family health and nutrition. In India, 60–80% of the rice-farming operations are carried out by women (Paris and Luis 1990). Unfortunately, recognition of this fact has not yet led to concrete actions to aid women. Any effort to increase rice production and raise the living standard of poor rural households must address the needs of women as both producers and consumers. National policies are needed to support women, both economically and in terms of social welfare.

Measures on behalf of women must simultaneously address various problems. It is not enough to target benefits to the poor in the hope that women will automatically gain. Measures must be aimed directly at women, either through specific projects or through project components designed especially for them. Such projects should be integrated into an overall development process and should elicit the support of society as a whole. Strategic research to benefit rural women must be designed to provide an organizing principle within a policy framework. This framework has six components: (1) the livelihood status of the farm or rural household, (2) time allocation between men and women, (3) control over resources between men and women, (4) control over income between men and women, (5) postharvest and marketing activities of women, and (6) prices and markets for labor, inputs, and outputs.

Policy on inputs and mechanization could offer potential for taking gender into account. The main issue would be the provision of information to women on inputs, because women are chiefly responsible for their application on the farm. For agriculture in general, some guarantee of women's security in land tenure and access to credit is needed. The nation urgently needs to take initiatives, either by the Ministry of Agriculture alone or in consultation with the Ministries of Labor and Human Resource Development, to launch a program on Women in Rice Farming Systems (WIRFS), which would focus on women's needs as partners in rice production.

## Information systems requirement

Information systems are essential from the natural resource base to the spatial dimensions of rice production and consumption. Inventory management under optimal transportation models becomes important here, along with improved storage, seasonal aspects of the crop season, and postharvest assessments of stocks and prices. Social adjustment programs of short-term employment and income generation may need to be developed. Databases on labor market trends, information on successful community intervention strategies, and mechanisms for identifying truly needy populations at the household level will also be required.

Food storage, cooking, and consumption habits should be studied and local technologies—either traditional or new—identified, with application possibilities for resolving food gaps in an efficient manner. Planners need to know about delivery systems that work, particularly market channels integrated with community efforts or public objectives.

## National decision making

Critical decisions at the national level will have to be made on the planning and distribution of rice production. The kinds of decisions will be as follows (Alagh 1994, 1995):

- The purchase of food items in international markets, or establishing access, for example through "future" markets, or recourse to bilateral or multilateral agencies for food aid or cereal facilities.

- Decisions on adjusting domestic stocks through national policies, which may include the purchase or sale of public stocks and attempts to influence private inventories, and the related question of desired levels of domestic prices of rice.
- The use of support prices, tariff mechanisms and domestic taxes, restrictions, and subsidies.
- Optimal internal stock movements and the related question of domestic availabilities and price spreads in regional markets.
- Access and vulnerability among consumers, for example in *mofussil* (rural) areas, or categories such as women, children, the unemployed, and the destitute or disabled.
- Short-run decisions on financing, credit, and foreign exchange requirements of operational food policies.
- Decisions with a medium-term horizon such as the assessment of food demand, incentives and support policies for domestic producers, the development of an improved processing and marketing infrastructure, standardization, nutrition and quality, and employment and income supplements for marginal populations.

### State decision making

Decision making at the state level is also critical. Examples of needs follow:

1. Long-term

- Consistent information on prices and qualities of marketed agricultural products, retail prices by location, estimates for rice production area, yield and forecasts for current seasons, and quality standards and prices for government and private stocks.
- Data on population, sex, and age distribution, and forecasts to prepare indications of vulnerable or at-risk segments of the population.
- Aggregation and regular updating of information on food accessibility and regional markets.

2. Medium-term

- Expansion of supply.
- Marketing and trading, infrastructure communication, and data networking facilities for interactive communication.
- Inventory and storage management and postharvest assessments of stocks and prices (Govardhan and Rao 1996).

## Developing political support

Political will and support are essential instruments for the effective implementation of a policy of sustainable rice production and distribution for self-sufficiency in India. Although the courage of convictions that change is necessary lays the political foundation for reform, action is made possible only through specific knowledge of what can be done. Without knowing what the options are for addressing a problem, the conviction that it needs to be addressed may not result in any particular action.

Indeed, the initial conviction may be lost. Understanding realistic policy options requires knowledge, which must be diffused.

Developing and implementing either a prescriptive or holistic policy plan for sustainable rice production and distribution in India will require cooperation and coordination among the central and state ministries of agriculture, and the ministries of civil supplies, finance, planning, and health, in addition to a high level of political support. Whereas policy analysis is a fact-finding process, food policy decisions are politically sensitive and the essential decisions must be made by leaders. The Indian Council of Agricultural Research facilitates decision making by conducting research through various models. The National Institute of Rural Development, Hyderabad, in consultation with the Indian Council of Social Science Research (ICSSR) and the Indira Gandhi Institute for Developmental Research (IGIDR), Bombay, is making a serious effort to work out different avenues of food accessibility by considering poverty level as an indicator.

In general, conviction of the need for reform generates political support. This support must be buttressed by relevant knowledge that is diffused to policymakers and consolidated through education and training. A good deal is known about incentives for increasing production, about the introduction of new agricultural technologies, and about ways to take into account the market position of the poor and the marginalization of disadvantaged, small subsistence producers, including women.

Although more research is important, it should not be used as an excuse to delay assistance in helping relieve food deficits and hunger. There is an immediate need to bring forward what is already known from past experience and to capitalize on the high political concern about food problems in different regions of India. People living at the subsistence level need help now. Can we draw on what is known about what works effectively to create new, imaginative programs while working simultaneously to build and strengthen the knowledge base? Unless we do, mobilizing political support in itself will not be enough to get the job done. Although the government now broadly recognizes the need to deal more effectively with emerging food problems, knowledge of how to do so is often inadequate.

## Sustainability determinants

Rice sustainability determinants can be categorized as physical, biological, and socioeconomic. Physical determinants are soil, water, atmosphere, chemicals, and energy. Biological factors relate to genetic resources, pests, and animal nutrition and health. Socioeconomic determinants include political commitment, economic policies and price structures, infrastructures and markets, inputs, credit, research, extension, education, tenure, regulations, labor availability, and household survival and capital accumulation strategies. These determinants need to be characterized for specific agroecological zones (AEZs), a concept congruent with both FAO's work on AEZs and the international agricultural research centers' (IARC) ecoregional approach. The AEZs appropriate to rice-based cropping systems are the irrigated, rainfed upland, rainfed lowland, and flood-prone zones. which have a wide range of technological options.

Location-specific technology assessments should relate to the production systems within a particular agroecological zone. Such systems (possibly farm households) are an appropriate unit for evaluating sustainability because they can be well specified. The combination of agroecological zones, resource endowments, and production-systems characterizations will ultimately define technology recommendations. Technology application is not governed entirely by biological and biophysical determinants, however; often, the policy environment dominates. Policies on input and output prices and subsidies can distort the application and deployment of production resources. This fact is evident from the large differences in rice yields that occur within a given climatic and biophysical environment, indicating that socioeconomic factors themselves can dictate varying levels of production.

The general objectives of research and technological interventions are food security and risk resilience, environmental compatibility and ecological security, economic viability, and social acceptability. But the various AEZs and production systems require location-specific solutions. Thus, in rice-based cropping systems, some of the major issues are soil degradation and inefficient use of inputs, including water. Other indicators of nonsustainability include a high incidence of pests, salinity and waterlogging, decreased organic matter content, declining soil fertility, and the excessive use of agrochemicals. These indicators guide the choices for technological interventions. Several rice-based cropping technologies (both information-based and material-based) are available, while others are needed (Table 16). The analysis of nonsustainable indicators should lead to definable objectives and technological options. To promote the wider assessment and transfer of successful technologies, location-specific lists should be prepared and shared nationally and internationally.

## Technology transfer and sustainable rice systems

Technologies classified as information-based, material-based, or emerging future-need-based can help. Most Indian rice farmers have limited capital. For them, nonmonetary information-based technologies will be most appropriate. The transfer of such technologies is complex and difficult because it involves mass participation, a continuous flow of up-to-date information, and multidisciplinary and multisectoral linkages. Thus, a participatory farmer-first approach should be the new paradigm of technology transfer (Table 17). Human resource development for training and extension then becomes important. These interventions also require changes in a number of existing policies.

Material-based technologies include items such as seeds of improved varieties, new fertilizer mixtures, pesticides, farm implements, and postharvest equipment. Such technologies need to be low-cost and accessible to rice-growing farmers.

Emerging future technologies, perhaps based on biotechnology and information science, should also be explored further (Table 18). Mechanisms are needed to ensure that new technologies are readily accessible to all interested farmers and institutions.

**Table 16. Available and needed technologies for sustainability of rice production and consumption.**

| Available technologies | | |
|---|---|---|
| Information-based | Material-based | Needed technologies |
| Knowledge of IPM[a] and IPNS | Appropriate varieties | Biofertilizers |
| Knowledge of biocontrol | Farm implements and machines | Transgenes and other biotechnology applications |
| Integrated rice-based crop-livestock system | Soil amendments | Tolerance of abiotic stress |
| Water management | Rehabilitation of conveyance and drainage systems | Crop modeling |
| | Agrochemicals | Effective physiological parameters, processing, and by-product processing |
| Green manure | Resistance to abiotic stress | Eco-friendly and environmentally acceptable packaging |
| Soil management | Legume fodder banks | Communication network systems |
| Agronomic practices (timely sowing, fertilizer placement, etc.) | Sown pastures/fodders | Information technology |
| Regulated markets and PDS | Market yards | Energy |
| Storage, processing, and distribution | Rice milling technology | Transportation |
| Rural business environment | Godowns[b] and transport | Wholesaling |
| Wholesaling | Infrastructure-transport communication | Retailing |
| Retailing | | |

[a]IPM = Integrated pest management, IPNS = integrated plant nutrient system, PDS = public distribution system. [b]Godowns are large-sized grain storage houses.

**Table 17. The different tasks in technology transfer for sustainable rice systems.**

- Promote farmer-to-farmer exchanges
- Provide better information for rice producers and consumers
- Encourage the adoption of natural resource accounting
- Encourage the formation of local rice groups and team building
- Foster rural partnership
- Encourage the formal adoption of participatory methods and processes
- Provide support for information systems to link research, extension, and farmers
- Strengthen capacities of NGOs to scale up
- Foster stronger NGO-government partnerships
- Provide communication for public distribution system beneficiaries
- Integrate modern tools of communication

Table 18. The rice production system and nonsustainability indicators.

| Aspect of production system | Nonsustainability indicators |
|---|---|
| *Nonsustainability issues* | |
| Input use, Irrigation, soil degradation, lack of market development | Pests and diseases, salinity, waterlogging, nutrient leaching and imbalances |
| | Decreased organic matter, excessive use of agrochemicals |
| | Drainage problems |
| | Lowered water tables, uncertain water availability, declining profitability, on-farm water management capacity |
| | Plateauing/declining yields, soil-plant-water pollution, production fluctuations |
| *Accessibility to rice as food* | |
| Lack of market development, credit, and financial institutions, targeted delivery system | Leakages from public distribution system, private business, and money lenders; transport; communication; market availability; milling technology; nutrition; health |
| | Fluctuating prices, support price, women's participation, cost of production, stock, and storage, labor migration |

## Potential research and development strategies through national efforts and international cooperation

### Systems approach

Rice requires a systems approach for sustainable development. This approach can be based on a research-technology delivery system that spans a continuum from basic to strategic, applied, and adaptive research, through a cogent analysis of technology adoption by farmers. NARS, IARCs, FAO, and other international and regional entities are active in this area. Specific roles and accountabilities for these partners could be established under a cooperative arrangement.

It is worthwhile to examine specific rice-based cropping systems technologies whose assessment, transfer, and support could be pursued through NARS-IARC-FAO collaboration. Two possible avenues might be technological interventions through ongoing programs in rice-growing countries, and the introduction and strengthening of activities in prospective rice-growing countries.

### Strategic research and cooperation

Basic and strategic research can be conducted by appropriately equipped NARS, IARCs, and collaborating institutes in industrialized countries. Such research may include developing hybrids and novel ideotypes, enhancing and characterizing germplasm, using biotechnological manipulations for durable resistance against pests and abiotic stresses, characterizing physiological parameters to improve selection efficiencies, formulating simulation models, developing biocontrol measures, and promoting biological nitrogen fixation. Continuous funding for such studies should be ensured. Additionally, regional and international cooperative mechanisms must ensure the free exchange of information and materials generated through such collaboration.

Rice-growing countries have extensive crop-oriented research and development programs. Rice-based cropping systems have generally been included as one of many components within a farming program. The importance of rice-based cropping systems to the agricultural and general economics of rice-growing areas suggests that budgets and personnel should be assigned specifically to these systems. It is essential for each NARS to strengthen its capabilities to analyze, investigate, and improve rice systems according to local needs and opportunities. Such programs need to be interdisciplinary and multicommodity, and should involve specialists in rice and wheat, as well as biological, physical, and socioeconomic scientists, and irrigation and extension managers.

### Cost-effective technologies

The FAO's conceptual framework and preliminary indicators for nonsustainability may help NARS to quantify and characterize the needs for technology adoption in rice systems (Table 18). FAO, in collaboration with the IARCs, could assist the NARS in developing suitable manpower through training. The new procedures for analyzing long-term fertilizer experiments should be incorporated into NARS programs and applied to all pertinent data sets. Data from regularly monitored farmers' fields could quantify trends in resource quality and sustainability. Additional long-term experiments should be established in various agroecological and socioeconomic zones to investigate a range of prospective technologies and their interactions, cost-effectiveness, and appropriateness for adoption.

### Development and policy intervention

Ongoing NARS (South Asia)—IRRI regional collaboration should be strengthened and expanded to allow it to identify valid indicators of system sustainability and to generate cost-effective technologies to increase the productivity of the region's rice systems. Farmers' yields are about one-half of demonstration yields. If farmers could increase their productivity, there would be no deficits in the region's rice production in 2000 and beyond. For those rice-growing countries that desire self-sufficiency, the required increase in productivity could be achieved through appropriate development support, extension policy interventions, and regional collaboration. The International Rice Commission and the Regional Commission on Food Security for Asia and the Pacific Region could help initiate and sustain the necessary endeavors.

## Policy formulation and planning

### Information availability

Policy formulation and planning for rice production depend critically on the availability of adequate information on the location and extent of rice-based cropping systems, resources used and their productivity and profitability, system trends, social aspects, and research and technology. A regional database should be established for collecting, collating, augmenting, and updating the existing and emerging information on rice-based cropping systems. The database should be accessible via modern information technology networks to all national and international entities that are able and need to use it.

### Resource use efficiency and management

Irrigation, fertilizer use, and agrochemical applications expanded rapidly after 1960, and high costs were involved. The use efficiency of these resources has often been low, and may have actually declined. Raising efficiency may require developing technologies based on integrated pest management, integrated plant nutrition systems, and integrated soil and water management. Local adaptation of such technologies (with farmer participation) and their popularization should receive the highest priority in research and extension programs. Policies on agrochemicals and water use would need adjusting, and greater demands would be made on management capabilities.

### Crop improvement and crop production technology

Genetic improvement of rice will continue to be a major component of technology development. Factors contributing toward sustainability include yield enhancement, increased input use efficiency, wide adaptability, and resistance to and tolerance of biotic and abiotic stresses. The application of biotechnology could further support genetic improvement of rice by finding solutions to problems that resist conventional approaches. There is also a need for strengthening research and technology on sustaining soil fertility and health, pest-disease management, and plant-water-nutrient interactions. These various activities merit a high priority on national and international research agendas.

### Input policy

Development agencies and the private sector must ensure that the inputs necessary for productive rice cropping are available. Key inputs include quality seeds of recommended varieties and also of green-manure species, fertilizers, field implements (including tractors and postharvest equipment), irrigation, and credit. Appropriate national and international policies, particularly for prices, subsidies, distribution systems, and land tenure, can strongly and favorably influence rice productivity and sustainability. National policy on exports, imports, and sufficiency in rice production is likely to guide decisions and actions for other interventions. Decisions to review subsidies and allow a stronger interplay of national and international market forces can ensure that production has a major influence on investment decisions. Certain subsidies—for the purchase of gypsum to amend sodic soil and water, for instance—might enhance the productivity of other inputs and hence overall system productivity. Other subsidies, such as for fertilizers and irrigation water, have encouraged overuse and misuse leading to environmental degradation and a diminished use of organic fertilizers.

### Policy research and technology development

To ensure that the complex policies, technologies, and infrastructural support needed for the sustained and enhanced productivity of rice systems are indeed forthcoming, there is a need for a continuing region-wide, multicommodity, interdisciplinary, interagency effort in research, extension, and on-farm support. Distribution and delivery systems need an overhaul supported by agencies and institutions.

We must find ways to create conditions for sustainable food security in general, and rice in particular, as a part of policy formulation and planning. Planning must emphasize information availability, resource use efficiency, input policies, policy research, and technology development. The greatest challenge will be to reform policy processes themselves. These will have to focus more on widespread participation and social mediation to counter the complexities and uncertainties involved in achieving the sustainability of rice production in India.

## References


Alagh YK. 1994. Indian development planning and policy. New Delhi (India): Vikas.

Alagh YK. 1995. Poverty and food security—towards framing a policy system for food security. Working Paper for Planning Commission, 172/1995.

Govardhan V, Hanumantha Rao C. 1996. Regreening of agriculture—Indian scenario. Planning Commission of India Report, XXIV/1996.

Paris TR, Luis J. 1990. Gender analysis in Asian farming systems research. Paper presented at the AFSRE Symposium, 1-17 Oct 1990, Michigan State University, East Lansing, Michigan.

Swaminathan MS. 1993. Challenges and opportunities in rice research: new frontiers in rice research. Hyderabad (India): Directorate for Rice Research.


## Notes


*Author's address:* Indian Council for Agricultural Research, New Delhi, India. rsp@icar.delhi.nic.in



*Citation:* Dowling NG, Greenfield SM, Fischer KS, editors. 1998. Sustainability of rice in the global food system. Davis, Calif. (USA): Pacific Basin Study Center, and Manila (Philippines): International Rice Research Institute.

CHAPTER 22

# Conclusions: a potential research agenda

S.M. Greenfield

The papers in this book provide an insight into the problems associated with the sustainability of rice production. This insight includes a sense of the knowledge required to more fully understand the problems. In addition, however, and possibly even more important, this insight gives us an ability to identify the areas where currently available knowledge and data are not adequate to meet the requirements and thus permits us to begin to structure an effective research agenda.

It is not the purpose of this chapter to develop a strategy that defines and specifies all-inclusive research programs and projects. If possible, I would like to develop an "ignorance matrix" that clearly identifies all the factors, and their interactions, that directly or indirectly contribute to the sustainability of rice and that, in each case, provides a sense of the current extent of the available knowledge and analytical tools. The availability of such a matrix could allow us to structure a detailed research agenda. Given our current inability to even fully identify all of the factors that can contribute to a determination of sustainability, it is not possible, unfortunately, to develop such a matrix at this time. I therefore intend to extract from the papers contained in this volume those areas where, based on the broad spectrum of expertise represented by the authors, there is an expressed uncertainty or an obvious lack of the knowledge required for definitive analyses. To the extent possible, I have included those areas where data are lacking and are thought to play an undefined role in the overall problem of sustainable rice production.

Examining the questions raised by the authors, which essentially constitute the recommended research agenda, we immediately notice that they are naturally divided into two basic categories. The first contains the general or global questions that consider the subject of rice sustainability within a broader context. The second category contains a more detailed set of questions that are primarily concerned with the specifics of rice yield. The questions in the second category more accurately reflect the current research efforts of the community of scientists concerned with programs directed at improving rice yield so as to continue to meet the growing demand. The questions in the first category constitute what may be characterized as a longer term, less structured research program that will raise many more questions, requiring study, as it unfolds. This, however, reflects the normal evolutionary process of a body of knowledge.

Several global questions have been raised in this book.

- Why have rice yields plateaued or even decreased during the past decade?
- What is the proportional role played by biological (genetic, etc.), physical (climate, etc.), and economic factors in determining annual rice yield?
- How do the factors that affect rice yield depend on cultural, geographic, and policy parameters?
- What are the local and regional social, economic, and institutional requirements and impacts as we attempt to meet the demands of rice sustainability? Can the trends in these requirements and impacts be modified if they are found to be unattainable or harmful?
- To what extent is there a time dependence for relevant rice yield factors and their impact on the system?
- What are the possible feedback processes between climate change and changes in rice production through altered emissions and atmospheric concentrations of greenhouse gases?
- What are the effects of intensified rice production on the hydrological cycle and the global cycles of C and N?
- What is the link between global climate change and biodiversity of the rice gene pool?
- What is the adaptation potential of rice cultivation in coastal areas affected by a rise in sea level?
- Is it possible to stabilize yields and prices in the face of annual variations in climatic factors (positive and negative effects of economic factors on rice yield—a global approach)?
- What determines the yield of a given soil under a given climatic regime and a given growth history?
- What is the effect of urbanization on rice production?
- How can we determine the profiles of future demand for rice for various agroecological and economic regions? What, for example, is the effect of increasing family income on the demand for higher-quality rice? What is the effect of changing diets on the future demand for rice?
- If we can equate increasing family income with an increasing demand for higher-quality rice, how does this affect the sustainability of rice production?
- Can we protect and improve water quality and increase water use efficiency without adversely affecting crop yield?
- Is it possible to improve the water quality of a region (watershed) and increase water use efficiency without adversely affecting nonfarm users of this same resource?
- Can we more effectively take into account geographic differences in rice-growing areas to maximize the use efficiency of increasingly scarcer water resources in the rice-growing regions of the world?

Several more specific questions follow.

- What is the long- and short-term impact of soil chemistry on rice production and sustainability?
- What are the long-term effects of currently promising approaches to increasing rice yield (i.e., genetic manipulation, breeding strategies, etc.) on biodiversity, rice quality (from a consumer's standpoint), and rice vulnerability?
- In connection with the preceding question, what is the value of on-farm conservation for protecting rice genetic resources, and what should the balance be between *ex situ* and *in situ* conservation?
- What is the effect and geographic distribution of global environmental change on rice yields (e.g., temperature and precipitation variations, changes in $CO_2$ concentrations, changes in the availability of nutrients, increased UV-B radiation, etc.)?
- What is the effect on the agronomic sustainability of rice of disturbing the established equilibrium among system components and functions (e.g., the impact of intensive cultivation of irrigated rice land)?
- What is the impact on rice yield of improvements in tolerance of abiotic stresses (flooding, salinity, drought, etc.)?
- What is the potential for developing and implementing strategies for new crop and environmental management techniques, and their potential impact on rice yield?
- How can the methods of wet and dry seeding be most effectively applied to increase water use efficiency and crop yield?
- What is an effective strategy for the reliable establishment of direct dry-seeded crops with adequate control or suppression of weeds?
- How can we better understand root growth and water extraction in various rice environments, and what are the potentials and opportunities for genetic enhancement?
- How do we integrate/link, in the most beneficial manner, rice with other local crops and cropping systems?
- What are the kinetics of nutrient supply and flow, particularly in intensively cultivated irrigated rice lands?
- Can we quantify the sustainability of the biocatalytic functions in the soil environment?
- What are the biological alternatives to chemical weed and pest management in rice lands (e.g., allelopathy research on cultivars to aid in weed management, etc.)?
- What are the limitations on developing better approaches to the transfer of technology to the farm level, including the ability to apply knowledge-intensive management practices?
- What methods can be developed and applied to measure and determine how knowledge is absorbed, acted upon, and transferred on a farmer-to-farmer basis?

- What is the potential role of organic farming in helping to attain the sustainability of rice yields?
- What is the impact of individual farm family income on rice yields?

A final area of concern involves the ability to ultimately “model” rice production problems in terms of integrated supply and demand issues (i.e., the role of rice in the global food system). In this case, we are forced to consider the social, cultural, economic, and infrastructure issues in concert with the technical agricultural issues, all of which have been discussed individually and recommended previously. We recognize that the correctness of the results can only be as good as the degree of certainty with which we consider the interactions and interfaces among these various issues,

There is no question that many attempts have been made to develop and use models to consider various constructs of the rice production and distribution system. Given the lack of data and knowledge on what constitutes the complete set of component parts and how they act and interact, however, it is understandable why no attempt has yet been made to develop a model(s) that encompasses the entire supply and demand system. Even those that have been developed successfully to usefully treat major portions of the rice production system have been forced to assign parameters to major segments and, using correlative techniques, allow for the use of incomplete data or the lack of adequate knowledge or understanding. It is clear, however, that having models with the capability to consider the entire system, and obtaining the data and knowledge necessary to have confidence in the results, would further our understanding of both the problems and their potential solution. (It should be noted that we talk of models rather than a single model to recognize that in the extreme it may be necessary to categorize certain parameters in a manner that precludes the use of a single model.)

For this reason, a primary research area must be one that attempts to describe and acquire the data and knowledge required to understand not only the component parts of the rice production and distribution system but also how they interact. Further, this effort to establish the necessary knowledge and database must build on the work already accomplished by a number of researchers so as to ultimately lead to the development of an effective operational model(s).

It is also clear that in the interest of policy formulation and planning as well as simulation modeling, a regional database should be established for collecting, collating, augmenting, and updating the existing and emerging information on rice-based cropping systems. This database, once established, should be accessible via modern information technology networks to all national and international entities that are able and need to put it to use.

In conclusion, as inferred above, given our current state of knowledge of the dynamics of sustainability, even the generalized listing of research areas of interest cannot be considered to be all-inclusive. Rather, it represents a studied step toward acquiring an ability to effectively solve these difficult problems. Obviously, many more steps must be taken.

## Notes

*Author's address:* San Francisco State University, San Francisco, California, USA. sgreenfield@earthlink.net

*Citation:* Dowling NG, Greenfield SM, Fischer KS, editors. 1998. Sustainability of rice in the global food system. Davis, Calif. (USA): Pacific Basin Study Center, and Manila (Philippines): International Rice Research Institute.

# Appendix 1. List of participants

Shariff Bin Ahmad
MDSHARIF@MARDI.MY

R. Barker
Director, National and Special Programs
International Irrigation Management Institute
Sri Lanka
R.BARKER@CGNET.COM

M.R. Bellon
Economics Program
International Maize and Wheat Improvement Center
M.BELLON@ALPHAC.CIMMYT.MX

J. Bennett
J.BENNE'TT@CGNET.COM

Gerald Berkowitz
Professor and Department Head, Plant Science
GBERKOW@CANRl.CAG.UCONN.EDU

Howarth Bouis
H.BOUIS@CGNET.COM

Francesca Bray
BRAY@SSCF.UCSB.EDU

Stephen Brush
Professor, Human and Community Development
SBBRUSH@UCDAVIS.EDU

Colin Carter
Professor, Agriculture and Resource Economics
COLIN@PRIMAL.UCDAVIS.EDU

Kenneth Cassman
Department of Agronomy
University of Nebraska
Lincoln, Nebraska
AGRO001@UNLVM.UNL.EDU

Gelia Castillo
MLAGO@CGNET.COM

M. Cohen
M.COHEN@CGNET.COM

D.J. Connor
DJC@AGRICULTURE.UNIMELB.EDU.AU

Ken Dahlberg
DAHLBERG@WMICH.EDU

S.K. De Datta
S.DATTA@CGNET.COM

Noreen Dowling
NRMOINI@EARTHLINK.NET

Robert Evenson
ROBERT.EVENSON@YALE.EDU

Walter Falcon
HF.WPF@FORSYTHE.STANFORD.EDU

Ken Fischer
K.FISCHER@CGNET.COM

Larry Fisher
LAF2@CORNELL.EDU

Shu Geng
SGENG@UCDAVIS.EDU

Michael Glantz
GLANTZ@UCAR.EDU

Stan Greenfield
SGREENFIELD@EARTHLINK.NET

James Hill
Chair and Extension Agronomist
Department of Agronomy and Range Science
University of California, Davis
Davis, California
JEHILL@UCDAVIS.EDU

Takeshi Horie
F51381@KUDUTS.KUDPC.KYOTO-U.AC.JP

M. Hossain
M.HOSSAIN@CGNET.COM

Richard Howitt
REHOWITT@UCDAVIS.EDU

Sakda Jongawwattan
Multiple Cropping Center
Chiang Mai University
Thailand
SAKDA@CMU.CHIANGMAI.AC.TH

Kazuhiko Kobayashi
CLASMAN@NIAES.AFFRC.GO.JP

Gilbert Levine
GL14@CORNELL.EDU

Justin Yifu Lin
JLIN@PKU.EDU.CN

Peter Lindert
PHLINDERT@UCDAVIS.EDU

Chung-Ming Lui
Professor, Department of Atmospheric Sciences
Director, Global Change Center
National Taiwan University
LIUCM@CCMS.NTU.EDU.TW

Ron Miller
RMMILLER@SFSU.EDU

Roz Naylor
ROZ.NAYLOR@FORSYTHE.STANFORD.EDU

M. Olofsdotter
M.OLOFSDOTTER@CGNET.COM

R.S. Paroda
RSP@ICAR.DELHI.NIC.IN

S. Peng
S.PENG@CGNET.COM

David Pimentel
DP18@CORNELL.EDU

R. Pinderhughes
RAQUELRP@SFSU.EDU

L. Price
LISA.LEIMARPRICE@ALG.VSL.WAU.NL

Bill Rains
DERAINS@UCDAVIS.EDU

W. Reichardt
W.REICHARDT@CGNET.COM

Pamela C. Ronald
PCRONALD@UCDAVIS.EDU

Mark Rosegrant
M.ROSEGRANT@CGNET.COM

Cynthia Rosenweig
CCCER@NASAGISS.GISS.NASA.GOV

Vernon Ruttan
Regents Professor
Department of Applied Economics
University of Minnesota
St. Paul, Minnesota
VRUTTAN@DEPARTMENTAGECON.UMN.EDU

L. Sanint
Director, Fondo Latinoamericano de Arroz de Riego
Cali, Colombia
L.SANINT@CGNET.COM

K. Schoenly
K.SCHOENLY@CGNET.COM

Hiroshi Seino
Director, Division of Environmental Planning
National Institute of Agro-Environmental Sciences
Japan
HSEINO@SS.NIAES.AFFRC.GO.JP

A. Siamwalla
AMMAR@LEELAl.TDRI.OR.TH

Vaclav Smil
Department of Geography
University of Manitoba
Winnipeg, Manitoba
Canada
VSMIL@CC.UMANITOBA.CA

Gus Speth
JAMES.GUSTAVE.SPETH@UNDP.ORG

Daniel Sumner
Director, Agricultural Issues Center
University of California, Davis
Davis, California
DASUMNER@UCDAVIS.EDU

J. Edward Taylor
Professor, Agriculture and Resource Economics
TAYLOR@PRIMAL.UCDAVIS.EDU

R. Wassmann
R.WASSMANN@CGNET.COM

Vo-Tong Xuan
Vice Rector and Director
Mekong Delta Farming Systems R&D Institute
University of Cantho
Cantho, Vietnam
V.XUAN@CGNET.COM

Qifa Zhang
Professor
National Key Laboratory of Crop Genetic Improvement
Huazhong Agricultural University
China
QIFAZH@PUBLIC.WH.HB.CN

# About the authors

Ossmat Azzam has been a virologist in IRRI's Entomology and Plant Pathology Division since 1995. Her research interests lie in host-virus interactions and virus diversity and its impact on mechanisms of plant resistance. She has a PhD in plant pathology from Cornell University, USA.

Vethaiya Balasubramanian is an agronomist and coordinator of the Crop and Resource Management Network (CREMNET) and acting program leader for accelerating impact in IRRI's International Programs Management Office. His research interests are natural resources management, development and evaluation of decision aids, farmer participatory research, communication, and project development and management. He has a PhD in agronomy and soil science from the University of Hawaii, USA.

Mauricio Bellon is presently a human ecologist in the Economics Program at the International Maize and Wheat Improvement Center (CIMMYT) in Mexico. He was an affiliate scientist in the Genetic Resources Center at IRRI from 1995 to 1997. He was also an assistant professor with the Universidad Nacional Autónoma de México from 1990 to 1995. His research interests are the use and conservation of crop diversity in agricultural systems, and the social and environmental impacts of technology and development projects. He has a PhD in ecology from the University of California, Davis, USA.

John Bennett has been a senior molecular biologist in IRRI's Plant Breeding, Genetics, and Biochemistry Division since 1992. His research interests are apomixis, nitrogen and sulfur metabolism, and insect resistance. He was a lecturer in the Department of Biological Sciences of the University of Warwick, UK, for 10 years, and a scientist for the Brookhaven National Laboratory in New York for six years, and a senior scientist at the International Center for Genetic Engineering and Biotechnology in New Delhi for three years. He has a PhD in biochemical plant pathology from the University of Queensland, Australia.

Sadiqul I. Bhuiyan is IRRI's liaison scientist for Bangladesh and a water resources specialist in IRRI's Soil and Water Sciences Division. He has been with IRRI since 1977. His research interests are water use efficiency in rice production, water harvesting for rainfed agriculture, and the sustainability of the natural resource base and rice production systems. He has a PhD in soil and water engineering from Texas A&M University, USA.

Darshan Brar has been a plant breeder in IRRI's Plant Breeding, Genetics, and Biochemistry Division since 1987. His research interests are wide hybridization involving alien gene transfer, and cytogenetic and molecular characterization of introgressed alien chromosomal segments. He has a PhD in plant breeding from the Punjab Agricultural University in India.

Francesca Bray has worked on both the history and modern development of rice farming in Asia as part of an overarching interest in technology and society. She teaches in the Anthropology Department at the University of California, Santa Barbara. Her publications include *Science and Civilization in China. Volume VI.2. Agriculture* (Cambridge University Press, 1984), *The Rice Economics: Technology and Development in Asia* (Blackwell, 1986, reprinted by University of California Press, 1994), and *Technology and Gender: Fabrics of Power in Late Imperial China* (University of California Press, 1997).

Michael B. Cohen has been an entomologist in IRRI's Entomology and Plant Pathology Division since 1994. He is interested in the development and sustainable use of insect-resistant crops produced by conventional breeding and genetic engineering. He has a PhD in entomology from the University of Illinois, USA.

Kenneth A. Dahlberg has been professor of political science at Western Michigan University since 1966. His research interests are in food and fiber systems, the politics of ecology, and global agricultural development. He is a member of the Commission on Environmental Strategy and Planning of the World Conservation Union.

Swapan K. Datta joined IRRI in 1993 and is head of the tissue culture lab in the Plant Breeding, Genetics, and Biochemistry Division. His research interests are in the areas of haploid and transgenic rice breeding. He has a PhD in botany from Calcutta University, India.

Achim Dobermann has been a soil nutrient specialist in IRRI's Soil and Water Sciences Division since 1992. His research interests are soil nutrients, soil spatial variability, soil testing, geostatistics, geographic information systems, and modeling of soil fertility. He has a PhD in soil science from the University of Leipzig, Germany.

Noreen G. Dowling is associate director of the Pacific Basin Study Center (which is now part of the East Asia Center on Population, Resources, and Welfare—EACOPRAW—at the University of California, Davis) and senior research associate at San Francisco State University. She has a PhD in chemistry and has worked for more than 20 years in interdisciplinary areas of science and public policy at the University of California, Davis, USA.

Robert Evenson is professor of economics and director of the Economic Growth Center at Yale University. His research interests are in the economics of agricultural development, households, and technology. He has a PhD from the University of Chicago, USA.

Kenneth S. Fischer has been IRRI's deputy director general for research since 1991. He was head of the Physiology and Agronomy Unit and coordinator of the Asian Regional Maize Program for the International Maize and Wheat Improvement Center in Mexico, a senior lecturer in the Department of Agriculture at the University of Queensland, and deputy director general for research at the International Institute for Tropical Agriculture in Nigeria before joining IRRI. He is an agronomist who is interested in crop physiology for the adaptation and improvement of crops in the humid and semiarid tropics. He has a PhD from the University of Queensland, Australia.

Thomas George has been an agronomist seconded from the University of Hawaii to IRRI's Agronomy, Plant Physiology, and Agroecology Division since 1989. His research interests are nutrient management of cropping systems and biological nitrogen fixation. He has a PhD in agronomy and soil science from the University of Hawaii, USA.

Stanley M. Greenfield is a geophysicist who has more than 40 years of management and program experience in the environmental area. He was assistant administrator for research and development with the United States Environmental Protection Agency and head of the Environmental Sciences Department of the Rand Corporation for 21 years. He is presently senior research associate at the Pacific Basin Study Center at San Francisco State University, USA.

Mahabub Hossain is head of the Social Sciences Division at IRRI. Before joining IRRI, he served as the director general of the Bangladesh Institute of Development Studies. He worked as a visiting scientist with the International Food Policy Research Institute (IFPRI) in Washington, D.C., where he published the IFPRI *Program Reports on Evaluation of the Grameen Bunk Credit Program and the Development Impact of Rural Infrastructure.* He is a coauthor of the books *Rice Research in Asia: Progress and Priorities* (CABI and IRRI, 1996) and *Asian Rice Bowls: The Returning Crisis* (CABI and IRRI, 1997). He has a PhD in economics from the University of Cambridge, England.

Ning Huang was formerly in charge of the genome mapping laboratory at IRRI, and is now with Applied Phytologics, Inc. His research interests are the genetic characterization of rice and the crop's molecular genetics. He has a PhD in genetics from the University of California, Davis, USA.

J.K. Ladha is a soil microbiologist in IRRI's Soil and Water Sciences Division. He joined IRRI in 1982. His research interests are biological nitrogen fixation, soil fertility and plant nutrition, integrated nutrient management, and sustainability. He has a PhD in soil microbiology from Banaras Hindu University in India.

Rhoda Lantin is a senior associate scientist at IRRI in the Soil and Water Sciences Division. She joined the institute in 1969. Her research interests are the chemistry of flooded soils, and trace gas emissions. She has an MS in food chemistry from Iowa State University, USA.

Justin Yifu Lin is professor and founding director of the China Center for Economic Research at Peking University. He has also been a reader at the Department of Economics, Hong Kong University of Science and Technology. He is active in debates on policy in China. His research interests are institutions, technology, and development policy. His research is supported by a Rockefeller Foundation Grant for rice production constraints in China. He has a PhD in economics from the University of Chicago, USA.

Bao-Rong Lu has been a germplasm specialist in IRRI's Genetic Resources Center since 1994. His research interests are germplasm conservation, systematic botany, cytogenetics, and taxonomy of wild species of rice, wheat, barley, and rye. He was a university teacher and lecturer in China for six years. He has a PhD in systematic evolution from the Swedish University of Agricultural Sciences.

Twng Wah Mew has been a plant pathologist at IRRI since 1975. He is also head of the Entomology and Plant Pathology Division and head of the Seed Health Unit. His research interests are bacterial diseases, host-plant resistance, biological control, and seed-borne pathogens. He has a PhD in plant pathology from the University of Minnesota, USA.

Tolentino B. Moya was an affiliate scientist in the global climate change project in IRRI's Agronomy, Plant Physiology, and Agroecology Division from 1994 to 1996. His research interests are elevated $CO_2$ and temperature influence on crop productivity, soil and water resources management and conservation, soil-crop-water relations, and crop modeling. He has a PhD in agricultural engineering from Cornell University, USA.

Maria Olofsdotter joined IRRI in 1994 with the task of working with allelopathic potential in rice germplasm. She is presently an affiliate shuttle scientist working with both the university in Denmark and IRRI (in the Agronomy, Plant Physiology, and Agroecology Division) on the development of allelopathic rice cultivars. She has a PhD in weed science from the Royal Veterinary and Agricultural University in Denmark.

R.S. Paroda is director general of the Indian Council of Agricultural Research and secretary of the Department of Agricultural Research and Education, Government of India, in New Delhi. He is the author or coauthor of more than 200 research papers, articles, and bulletins. He is presently chairman of the Governing Board of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), India. He has a PhD in plant breeding and genetics from the Indian Agricultural Research Institute.

Shaobing Peng has been a crop physiologist in IRRI's Agronomy, Plant Physiology, and Agroecology Division since 1991. His research interests are the physiological basis of yield potential, nitrogen nutrition and management, and gas exchange and photosynthesis. He received the Promising Young Scientist Award from the Consultative Group on International Agricultural Research in 1996. He has a PhD in crop physiology from Texas Tech University, USA.

Jean-Louis Pham has been a geneticist in IRRI's Genetic Resources Center seconded from the Institut français de recherche scientifique pour le développement en coopération (ORSTOM) since 1995. He has worked as a plant geneticist for ORSTOM since 1982, including seven years in Côte d'Ivoire. His research interests are plant population genetics, genetic diversity, and the dynamic conservation of plant genetic resources. He has a Doctorat en Sciences in plant genetic resources and breeding from the Université Paris-Sud Orsay, France.

Colin Piggin joined IRRI in 1995 as leader of the Upland Rice Program. He is now also leader of the Rainfed Lowland Rice Program. He has worked as an agronomist and weed scientist in the Philippines, Indonesia, China, and Australia over the past 20 years. His research at IRRI concentrates on weed biology, competition, and zero tillage. He has a PhD in weed ecology from the University of Melbourne, Australia.

Lisa M. Leimar Price worked at IRRI from 1994 to 1997 as an anthropologist in the Social Sciences Division. Her research interests are tenure and property, family systems, farmer knowledge, biodiversity, and gender. She has a PhD in anthropology from the University of Oregon, USA.

Wolfgang Reichardt has been a microbiologist in IRRI's Soil and Water Sciences Division since 1994. He has also served as an assistant professor at the University of Freiburg (Germany) and the University of Maryland and Oregon State University (USA), professor of ecotoxicology at Okayama University in Japan, and professor of microbiology at the University of Kuwait. His research interests are soil and water microbiology, ecotoxicology, nutrient cycling and fertilizer management, and rhizosphere microbiology. He has a DSc in biology, oceanography-biogeochemistry, and microbiology from the University of Kiel, Germany.

Serge Savary is a plant pathologist with the Institut français de recherche scientifique pour le développement en coopération (ORSTOM), seconded to IRRI, where he conducts research on risk analysis associated with rice pests and epidemiological modeling of plant diseases. He has worked for ORSTOM since 1979. He is a Doctor in phytopathology from the Wageningen Agricultural University, The Netherlands.

Veronique Schmit was an affiliate scientist in IRRI's Plant Breeding, Genetics, and Biochemistry Division from 1995 to 1998, working with the perennial upland rice project. Her research interests are plant breeding and phylogenetic studies. She previously worked for the FAO as an associate expert and researcher for five years, at the Centro Internacional de Agricultura Tropical (CIAT) in Colombia for two years, and as a bean breeder in Burundi for two years. She has a Doctoral degree in plant breeding from the Faculti des sciences agronomiques in Gembloux, Belgium.

Kenneth Schoenly has been an insect ecologist in IRRI's Entomology and Plant Pathology Division since 1996. His research interests are biological control, pest-natural enemy interactions, community and landscape ecology, ecological modeling, and forensic entomology. He was a university teacher, lecturer, and assistant professor for ten years. He was a Rockefeller Foundation Environmental Fellow in International Agriculture for three years. He has a PhD in ecology and evolutionary biology from the University of New Mexico.

Dharmawansa Senadhira was a plant breeder in IRRI's Plant Breeding, Genetics, and Biochemistry Division from 1985 until his tragic death in a traffic accident in July 1998. He was also leader of the Flood-prone Rice Program and IRRI representative for Thailand. His research interests were varietal improvement for flood-prone areas, and abiotic stresses. He obtained his PhD in genetics from the University of California, Davis, USA.

John Sheehy has been a crop ecologist and crop modeler in IRRI's Agronomy, Plant Physiology, and Agroecology Division since 1995. His research interests are crop modeling, systems analysis, ecology, environmental physics, nitrogen fixation, crop physiology, yield-limiting factors, instrumentation, and scientific innovation. He has been a scientist in different research institutions and universities around the world for 30 years. He has a PhD in agricultural botany/physics from the University College Wales, UK.

Vaclav Smil has been doing interdisciplinary research at the University of Manitoba, Canada, since 1972, concentrating on interactions of environment, energy, food, population, economics, and public policy. He has published more than 200 papers on these topics in more than 50 different journals, and he is the author of 15 books, the latest of which are *China's Environmental Crisis* (M.E. Shape, 1993) and *Global Civilization and the Biosphere* (Scientific American Library, 1996). He has a PhD from the College of Earth and Mineral Sciences of Pennsylvania State University, USA.

James Gustav Speth has been director general of the United Nations Development Programme since 1993. He previously worked for the National Resource Defense Council, the President's Council on Environmental Quality, and the Georgetown Law Center, from which he founded the World Resources Institute in 1982, and was its president from 1982 to 1993.

To Phuc Tuong has been a water management engineer in IRRI's Soil and Water Sciences Division since 1991. His research interests are agrohydrology, water use for land reclamation, and land and water resources planning and management. He has a PhD in soil and water engineering from the University of Canterbury, New Zealand.

Leonard J. Wade has been a crop physiologist/agronomist in IRRI's Agronomy, Plant Physiology, and Agroecology Division since 1993. He worked for 19 years as a crop agronomist, research agronomist, and principal scientist for the Queensland Department of Primary Industries. His research interests are drought resistance, genotype by environment interactions and selection, establishment and seedling vigor, nutrient by water interactions, and crop simulation and risk analysis. He has a PhD in crop physiology from the University of Western Australia.

Reiner Wassmann has been seconded to IRRI's Soil and Water Sciences Division from the Fraunhofer Institute for Atmospheric Environmental Research in Germany since 1993. His research interests are investigating atmospheric trace gas fluxes in various ecosystems, and implementing an interregional network on methane emission from Asian rice fields. He has a PhD in biology from the University of Gottingen, Germany.

Alan Watson is seconded to IRRI's Agronomy, Plant Physiology, and Agroecology Division from McGill University in Montreal, Canada, where he is a professor of agronomy in the Department of Plant Science. He splits his time equally between IRRI and McGill University. After he arrived at IRRI in 1991, he established a biological weed control program in rice-based cropping systems in Southeast Asia. He has a PhD from the University of Saskatchewan, Canada.