Rice in the Global Economy:

Strategic Research and Policy Issues for Food Security

Edited by
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IRRI

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

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Foreword

Rice is the most important food crop of the developing world. It is the staple food of about half the world's population. Roughly 900 million of the world's poor depend on rice as producers or as consumers. On average, rice accounts for nearly half of the food expenses of poor people and a fifth of their total household expenses. It is well established that the rapid productivity growth of rice resulting from the use of improved varieties, fertilizers, and irrigation (popularly known as the Green Revolution) increased production and led to a long-term decline in rice prices. This has been the major factor helping to reduce poverty in Asia over the past several decades.

Despite the past achievements, rice productivity growth will remain essential in the future for several important reasons. Rice yield growth has slowed considerably in recent years and has failed to keep up with population growth, leading to shortages and higher prices that have adversely affected the poor. This was demonstrated by the food crisis and the rice price spike experienced in 2008. Clearly, food security remains somewhat tenuous despite the rapid economic growth experienced in many parts of the world.

The ongoing changes in the economy, resource competition from other sectors, environmental changes, increasing commercialization of rice farming, and the importance of international trade mean that the way rice will be produced in the future will be substantially different. Some traditional rice-growing areas may lose their comparative advantage while others may become new growth centers for rice. Changes will also occur in gender roles in rice farming and demographic profiles of rice farmers as the nonfarm sector expands in the course of economic growth. These changes will have far-reaching implications for crop production and for social organization of the farm household economy. Clearly, there is a need to develop a new vision for future rice farming given these global trends and likely scenarios. This vision is needed to strategically position investments in rice research, technology delivery, and the design of policy reforms.

This volume attempts to provide such a vision for the future of rice farming. We considered it an opportune time to feature scholarly contributions from experts in the field to commemorate the 50th anniversary of IRRI's founding. Contributions in this volume cover various aspects of the global rice economy; new developments in rice production technologies and postharvest management; environmental issues; institutional innovations in technology delivery, rice marketing, and trade policies; and broader R&D policy issues.

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Robert S. Zeigler
Director General
IRRI

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Sushil Pandey
Chair, Editorial Board

Overview

Why another book on the rice economy?

Worldwide, rice is the most important food staple. It is grown on approximately 155 million hectares and accounts for one-fifth of the global calorie supply. Although traditionally an Asian crop, rice has long been a staple in parts of Africa and Latin America, and its importance is growing in those regions. Roughly 900 million of the world's poor (defined as those with daily income below US$1.25 in terms of purchasing power parity) depend on rice as producers or as consumers. Therefore, an abundant and stable supply of affordable rice is critical for reducing poverty and hunger.

Rice is one of the two crops (along with wheat) that spurred the Green Revolution. The Green Revolution led to higher productivity and incomes for farmers, greater demand for unskilled farm labor, and ultimately lower prices for consumers. These three characteristics brought large benefits to a wide swath of the population in Asia in particular and made a huge impact on global food production and poverty reduction.

Past success is no guarantee of a secure future. Rice yield growth has slowed considerably in recent years and has failed to keep up with population growth, leading to shortages and higher prices that have adversely affected the poor. Further, the problems of poverty and hunger still remain as huge development challenges. In addition, excessive and improper use of agro-chemicals, excessive draw-down of groundwater, and the impact of rice production on the emission of greenhouse gases such as methane continue to be important environmental challenges facing rice production.

Several earlier books have analyzed the challenges facing the global rice economy. An early account of technological stagnation in rice production and the likely consequences of rising population was provided by Vernon Wickizer and Merrill Bennett in their book *The Rice Economy of Monsoon Asia*, published in 1941. The *Asian Rice Economy* by Randolph Barker and Robert Herdt (1985) documented 25 years of changes in the rice economy due to rapid technological progress since the founding of the International Rice Research Institute (IRRI). Slightly over a decade later, *Asian Rice Bowls: The Returning Crisis?* by Prabhu Pingali provided a more sobering update, highlighting slowing yield growth and signs of serious environmental degradation.

So, why another book on the rice economy? The past decade has seen many changes that will shape the way food will be produced in the future. Rapid economic progress, especially in Asia, has led to rising wages and more diversified diets. The weather has always had important effects on production, but climate change may lead to particularly profound impacts. The food economy is now more integrated with other sectors of the global economy, including both energy and financial markets.

At the same time, despite rapid economic progress in many parts of the world, food security still remains somewhat tenuous. The 2008 world food crisis refocused attention on the need to ensure a stable, affordable, and sustainable food supply for the poor. There is a need to develop a new vision for future rice farming in the context of major global trends. Such a vision is needed to strategically position investments in rice research, technology delivery, and the design of policy reforms.

This book presents a new vision for the future of rice farming. The book is forward-looking and addresses the key strategic questions in the context of major developments in the global economy. Some of the strategic questions follow: (1) How does the role of rice change with economic growth? (2) Will rice be produced mainly on small or large farms; in irrigated or rainfed areas? (3) How will the increasing scarcity of labor affect the organization of rice production? (4) Can the poor depend on rice trade for stable food security? (5) Will Africa become the new growth center for rice? (6) What impact will climate change have on the way rice will be grown in the future? and (7) What are the key global and regional priorities for rice research and policy reforms? The various contributions in this book examine these questions in the context of major global trends.

The book consists of 18 chapters organized into four thematic sections: (1) rice in the global food economy, (2) organization of rice production and postharvest operations and input efficiency, (3) evolving rice market structure, and (4) technological opportunities and the role of R&D policies.

Whither the future of the global rice economy?

Predicting the future is always fraught with uncertainties and especially so in a world in which agriculture is increasingly linked to events in other sectors such as energy, water, and finance, leading to more frequent and severe supply shocks and unexpected new demands such as biofuels. Nonetheless, from the outset, this book has aimed to take a forward look at the global rice economy, with a focus on the next 10–15 years, but within a longer-run perspective to 2050.

Global rice demand and supply

Average global per capita consumption of rice has leveled off since the mid-1990s and may enter a period of long-run decline after a decade or so. This reflects several factors that diversify Asian diets away from rice—rapidly rising incomes, changing tastes with urbanization, and globalization, especially as younger people adopt a more "western diet" relative to their parents. Nonetheless, Timmer, Block, and Dawe (Chapter 1.6) show surprisingly heterogeneous trajectories of per capita rice consumption so it is difficult to make broad generalizations. Population growth in Asia that will slow from 1.1% in 2010 to an expected 0.9% in 2020 and 0.1% in 2050 may also decelerate demand growth for rice. On the other hand, demand is rising fast in Africa and in some other regions, where, as incomes rise, rice is replacing other food staples such as maize and cassava.

Despite the numerous uncertainties associated with making predictions about the future, both Timmer, Block, and Dawe (Chapter 1.6) and Mohanty, Wailes, and Chavez (Chapter 1.7) agree that *total* rice consumption will continue to increase until at least 2020 although their respective estimates range from 450 million tons to 475 million tons in 2020 relative to 435 million tons in 2008. Beyond 2020, there is considerable uncertainty about likely demand. Disaggregation of various structural shifts in consumption patterns and tastes results in a "best-bet estimate" of 360 million tons (Chapter 1.6) in 2050, which would represent a significant fall of 17% from today's level. Because per capita consumption falls with rising incomes, rice consumption will become more highly concentrated among the poor in Asia. Sub-Saharan Africa is a major exception to these trends and indeed Africa is likely to be a major driver of future growth in global consumption—although again with much uncertainty about demand projections beyond 2020.

At first glance, slowing or declining consumption levels for rice would seem good news to those who worry about global food security, given the dominance of rice as a staple food in much of the developing world. However, several significant trends on the supply side lead to a more challenging outlook.

First, the world, and rice farmers in particular, faces growing resource scarcity. Area sown to rice will probably start declining in Asia in the near future because of further urbanization and industrialization, but also in part because of the diversification of diets to vegetable oils, horticulture, and meat and dairy products, which are becoming more profitable alternatives to farmers (Pandey, Paris, and Bhandari, Chapter 1.4). There is large potential for expansion of rice area in Africa and Latin America: for example, wetland area suitable for rice in Africa is estimated at 240 million ha relative to current area of 3.5 million ha (Larson et al, Chapter 1.5). However, this land will come into production only if prices are substantially higher and countries are willing to depend more on trade. Likewise, severe social and environmental effects could be associated with large-scale expansion of rice cultivation in these areas. Increasing yields on existing land, also in Africa, must remain the highest priority.

Water scarcity is an even greater challenge, with total water supplies to agriculture unlikely to expand and with many aquifers already overexploited. Seventy-five percent of the world's rice production depends on irrigation, and these same irrigated areas are at a premium for crop diversification. Although the current global water footprint of rice is huge, recent technological advances such as water-saving irrigation or dry direct seeding will likely enable producing more rice with less water. Finally, agriculture more generally is facing scarcity of nonrenewable resources, especially fossil fuels that are the major cost item in the production of nitrogenous fertilizers.

Rice yields will have to increase to not only meet future population growth but also to compensate for a decline in area sown to rice. Yet, yield growth for rice has slowed from a peak of 3.3% in 1976-85 (vs. population growth of 1.7%) to 0.7% in 1998-2007 (versus population growth of 1.2%). This reflects many factors (Dawe, Pandey, and Nelson, Chapter 1.1, and Hazell, Chapter 1.3)—slowing investment in R&D, insufficient investment in irrigation, low marginal returns to additional fertilizer use, and a ceiling on yield potential of released varieties. The supply-demand model (Chapter 1.7) indicates that yield growth of 1.4% per year will be needed to keep rice prices at affordable levels ($300/t of milled rice) to around 2020.

Major uncertainties

More than at any time in recent history, it is the uncertainty that rice producers, consumers, and policymakers confront about the future that is perhaps even more critical than the overall projected trends in supply and demand. Two major sources of uncertainty are climate change and trade. Several recent efforts have been made to project the impact of climate change on agriculture. Globally, rice is one of the major crops affected largely because of its concentration in tropical and flood-prone areas. Predictions remain highly uncertain but scenarios are beginning to converge. Higher temperatures and drought incidence could reduce global rice yields by 12–14% by 2050, although the carbon fertilization effect (if it is real) from higher concentration of carbon dioxide in the atmosphere could mitigate some of this decline. However, these predictions do not capture other effects, especially the possibility of rising yield instability, farmers being forced out of rice due to water shortages, or probable loss of prime rice land due to more frequent flooding in the deltas where commercial rice production is concentrated (Wassmann et al, Chapter 4.1, and Barker et al, Chapter 2.4).

A further source of uncertainty is the future role of rice trade. Partly because of high trade restrictions, only 7% of global production is traded, an increase from the 1960s but still much lower than for other food grains. This together with erratic government interventions such as the 2008 export bans makes rice prices relatively unstable. With climate change and volatile energy prices, rice prices may become even more unstable. Yet, with measures that would increase trust in global markets, rice exports could significantly expand from regions with a relative comparative advantage, including Latin America and possibly eventually Africa.

Major structural changes

Major structural changes have taken place in the economy and livelihoods of people that have traditionally depended on rice farming. First, rice as a share of farm income is declining as rice farmers diversify to other crop and livestock activities to meet changing diets. In some more advanced rural economies traditionally based on rice, incomes from rice are now less than 15% of household income (e.g., Thailand; Chapter 1.4). Second, rural households are depending more on the rural nonfarm sector for their livelihoods. In densely populated Asia, half of household income is already provided from nonfarm sources, including remittances (Chapters 1.3 and 1.4), and these trends will only accelerate. Depending on rice policies, very small farmers will find it uneconomical to grow rice and they will continue to shift to part-time farming and off-farm work, depending increasingly on the market to meet rice consumption needs. Third, associated with these changes, women assume a much greater and often dominant role in rice farming, often taking on tasks traditionally done by men (Chapter 1.4).

Fourth, in those parts of Asia with booming nonfarm economies, the agricultural and rural sectors are poised to enter a stage of massive decline in agricultural labor through rural-urban migration. China's agricultural labor force has just started to decline, following the Republic of Korea and Japan in earlier periods. These trends imply a rapidly aging farm population and a demand for farm consolidation through land rental or sales (Otsuka and Estudillo, Chapter 2.1). Rice price policies will be a major determinant of the speed of these adjustments. The earlier transformations in Japan, Republic of Korea, and Taiwan Province of China were slowed by a trend toward very high protection and subsidies for rice producers. There is some indication of similar trends in other rapidly growing countries, especially in India and Indonesia (Chapter 1.2). However, in many countries, rice is still a substantial share of expenditures of the poor (28% for the bottom urban quintile in Bangladesh) so that high rice prices to support incomes of rice farmers who sell to the market negatively affect the poor, including many rice farmers who do not produce enough for their own needs.

Together, these changes imply a decline in the role of rice in the rural economy and in consumer expenditures, but with significant variations among countries in the pace of such a decline. However, it is certain that, well into the future, rice will remain important for farmers and consumers, especially for poor consumers, and consequently for national and global food security. This is even more so in sub-Saharan Africa, particularly in the low-income rice staple economies of West Africa. Given rice's dominance in the rural landscape, it is also central to the maintenance of healthy ecosystems and the environment.

The five major elements of a vision for the global rice economy

The chapters in this book lay out a vision for rice scientists and policymakers as they confront the future. This vision is determined by success in five major areas:

1. *Meeting global food security needs by providing an affordable and stable supply of rice:* Rice remains the most important staple in the developing world. As such, it is critical to global food security. On the surface, it would appear that the biggest challenge is to meet increasing rice consumption to around 2020-25. However, even if rice consumption may decrease beyond 2025, the challenge will be to increase yield to compensate for *declining rice area*, as land is diverted to other crops to meet changing diets and nonfarm uses, and for the increasingly negative impact of climate change. Equally important for global and national food security is to manage price volatility in the face of increasingly frequent and severe shocks from water scarcity, energy prices, and climate change.
2. *Successfully managing structural changes:* Asian rice economies are poised for major structural changes. These involve immense challenges to balance

consumer and producer interests and manage growing rural-urban income disparities. The design of rice-pricing policies will be at the heart of this change in order to continue to make gains in reducing rural poverty in South Asia and Africa, where most of the poor are concentrated. Rice price policies will also influence the pace of diversification of rice-farming systems and household incomes to nonrice farming and nonfarm employment. Finally, an unprecedented challenge in managing structural change is to facilitate land consolidation and mechanization to accommodate the exit of millions of people from rice farming.

3. *Enhancing efficiency in input use and value chains:* Another measure of success is to do more with less in all aspects of rice farming and along the value chain more generally, to both reduce costs and reduce damage to the environment. This entails major gains in the efficiency of use of water and fertilizer and reductions in pesticides by substituting better management and information adapted to the plot level and adjusted to seasonal conditions and crop growth. Fortunately, the low efficiency of input use in most systems provides much scope for improvement (30% gains in nitrogen fertilizer and water-use efficiency are quite possible with recently developed technologies), and higher prices and increased scarcity of these inputs may provide the incentives to realize these improvements. Higher efficiency must extend along the value chain, through better postharvest management and, especially in Africa, better functioning of input and output markets. Far too much rice is lost after harvest.
4. *Reducing environmental footprints:* The higher plot-level input efficiencies noted above will be an important step toward reducing the environmental footprint of rice farming, particularly water consumption and the flow of reactive nitrogen compounds. But, beyond the plot level, the challenge will be to better manage rice-based ecosystems to reduce water pollution, soil erosion, and downstream silting, while saving land and biodiversity. Globally, rice systems can contribute strongly to the mitigation of global warming through reduced emissions of greenhouse gases, especially methane and nitrous oxide, as well as sequestration of atmospheric carbon in soil organic matter.
5. *Addressing lagging regions (including Africa):* A final indicator of success is improved productivity and livelihoods in the lagging regions, especially rainfed rice and uplands where some of the poorest people are concentrated—but without neglecting the need for continued investment in productivity growth in irrigated areas. With pressure on irrigated areas to diversify to high-value products, rainfed lowland areas may gain a comparative advantage in rice production in parts of Asia. Development pathways for rainfed uplands and the role of rice in them will vary greatly. These regions, often populated by ethnic minorities, face many challenges, including a lack of infrastructure, poor institutions and governance, and fragile soils. Many are also vulnerable to the effects of climate change. The rapidly growing demand for rice

in Africa and low productivity of existing rainfed and upland systems also pose a huge challenge for rapidly accelerating rice productivity there.

What needs to be done

The chapters of this book lay out a rich menu of options for sustainably improving rice systems and enhancing overall performance of the global rice economy to reduce poverty and hunger. Priorities will clearly differ greatly among countries and even within countries. They will also necessarily embrace a wide range of technological, policy, and institutional options. Yet, several broad priorities emerge from this book. Global problems need global solutions, but they must be flexible enough to meet local needs.

Research for development

Increasing yield potential and yield stability, closing yield and efficiency gaps, reducing postharvest losses, and adding more value to cropping or farming systems constitute clear opportunities to enhance rice production, increase farmers' income, and do good for the environment. Increased investments are needed to realize some "quick wins," but also address the "best-bet" technologies needed 10 or 20 years from today. Nearly all rice farmers worldwide depend on rice varieties that have been improved by scientific breeding since the Green Revolution. Rice breeding is a slow process, but new technologies have cut the time needed to test and validate new varieties by about 30%, and this trend is likely to continue to reduce the time from trait identification to varietal transfer. Scientific advances in genomics and marker-assisted breeding mean that genebank materials can be explored on a large scale to identify and embed the genes responsible for ever more complicated target traits. Transgenic technologies offer the potential to engineer new plants that were previously unthinkable, such as rice using a new photosynthetic pathway. Meanwhile, improvements in sensors, processing, communications, and possibly nanotechnology offer the potential to revolutionize how field experiments are conducted, and may also enable a precision-agriculture revolution in input-use efficiencies. New information and communication technologies have made the time ripe for maximum exploitation of the economies of scale possible in rice research.

Yield potential. Increasing the yield potential of rice remains a priority of critical importance because yields in many of the most productive rice-producing areas in Asia are growing slowly or are stagnating as average farm yields approach 70–80% of the current yield potential ceiling. Yet, until now, increasing the yield potential of tropical rice varieties has been surprisingly elusive considering the importance of this trait (Mackill et al, Chapter 4.2). Some progress has been made in breeding "super rice" with higher yield potential in China, based on new plant-type concepts developed at IRRI about 20 years ago. Renewed efforts and much larger, sustained investments are needed to accelerate research on increasing yield potential, simultaneously through three major strategies:

1. Increasing the yield potential of inbreds by at least 10%. Molecular breeding approaches that rely on recurrent selection and a more systematic focus on direct selection for yield improvement in segregating generations of crosses will play a major role in this.
2. Further improvement of yield heterosis in tropical hybrids to achieve consistent yield advantages over the best inbred varieties of at least 20% through better understanding of the genetic basis for heterosis and using specific heterotic groups for targeted breeding.
3. Radical re-engineering of photosynthesis to turn the rice plant into a C_4 plant and thus increase yield potential by 30–50%.

Increasing yield stability and adapting to climate change. The sea-water level, temperature, and precipitation changes that accompany climate change, including more frequent climatic extremes, will require farmers to adapt (Chapter 4.1). Several approaches of germplasm development and improved crop and resource management can be deployed for reducing the vulnerability to climate-induced stresses, ranging from new germplasm with increased stress tolerance to shifts in crop management practices or greater diversification of cropping systems.

Exciting progress has been made in recent years in using molecular breeding approaches for increasing tolerance of abiotic stresses and resistance to some biotic stresses (Chapter 4.2). Particularly for farmers in poor, unfavorable environments, this results in greatly reduced risk of crop loss and increased yield stability. Marker-assisted breeding methods have been widely used to upgrade existing "mega-varieties," but will also be increasingly used in developing new varieties with trait packages designed for greater yield stability. Such genetic improvements, particularly with regard to traits such as tolerance of drought, submergence, salinity, or heat stress, are the key entry points for adapting to climate change and climatic extremes. They also encourage farmers to invest more in improved crop management practices, resulting in further increases in yield and income.

Many challenges remain. A massive, global genotyping-phenotyping effort is needed to discover new genes or quantitative trait loci (QTLs) conferring tolerance of major abiotic and biotic stresses. Breeding programs need to be transformed into targeted, product-oriented breeding pipelines that make full use of high-throughput molecular marker applications for equipping new varieties with the desired gene combinations. Epigenetics is emerging as a new research area, that is, the need to better understand the stability of gene expression in different genetic backgrounds and environments. Gene pyramiding will become common, but the stability and durability of tolerance of abiotic stresses or resistance to biotic stresses in pyramided varieties and hybrids needs to be better understood. The potential of transgenic solutions versus conventional molecular breeding needs to be carefully evaluated. Variety release and seed systems in many developing countries need to be modernized so as to shorten the period from developing a new variety to peak adoption by farmers (Tripp, Hu, and Pal, Chapter 2.2).

Closing yield and input efficiency gaps. Gaps between yields currently obtained by farmers and what could be achieved with improved management and varieties are still substantial, certainly in Africa, but also in Asia and Latin America. These gaps typically range from 1 to 3 t/ha. Postharvest losses may be as high as 20%. Efficiencies of nitrogen fertilizer or water remain 30–50% below levels that can be achieved with best management practices. Labor input varies widely, from less than 10 person-days per hectare in the most mechanized areas to more than 200 person-days per hectare in small-scale intensive farming.

A number of "win-win" technologies that have a high probability of success for substantial impact within the next 5 to 10 years have been developed through research in the past 10–15 years, including conservation tillage systems for direct seeding, site-specific nutrient management practices that increase yields and profit while reducing environmental concerns (Gregory et al, Chapter 2.3), and alternate wetting and drying and other water-saving irrigation techniques (Chapter 2.4). These "quick wins" will require mostly adaptive research based on solid partnerships at the grass-roots level to adapt prototype technologies to local settings and gender concerns and disseminate them widely through a multitude of public-sector and private-sector channels. In intensive irrigated rice systems, an *agronomic revolution* that focuses on deploying these and other improved management technologies is the key strategy for securing sufficient rice supplies over the near to medium term.

Over the longer term, research must be conducted on designing the rice-based cropping systems of the future, managed with ecological intensification principles aiming at achieving an optimal balance of high productivity, high input-use efficiency, and reduced environmental impact. In many areas, this may fundamentally change the way rice is grown today, moving from labor-intensive, puddled, transplanted, flooded rice systems to mechanized systems with less tillage, dry direct seeding, and only occasional flooding. This will require more precise, science-based management technologies, but also solid basic research, particularly on aspects of soil and plant health. For example, improving the understanding of soil-pest-crop-management interactions will be the basis for developing the next generation of integrated pest management systems that minimize the use of pesticides and adequately protect against yield losses at high yield levels (Norton et al, Chapter 2.5).

Reducing negative environmental effects. Many of the best management practices now available also have large potential impact on reducing the environmental footprint of rice cultivation. Changing water management to water-saving irrigation is among the most promising options because, in addition to reducing the overall water footprint of rice, it is suited to reducing greenhouse gas emissions from irrigated rice, particularly methane. Conservation agriculture can conserve soil organic matter and thus also stop the loss of soil carbon from diversified rice systems such as rice-wheat. New site-specific nutrient management approaches have multiple environmental benefits: (1) they reduce the amount of reactive nitrogen cycling back into biogeochemical cycles, (2) they directly reduce N_2O and NH_3 emissions, (3) they reduce CO_2 emissions associated with manufacturing mineral fertilizer, and (4) they contribute to increased soil carbon sequestration via increased biomass production. New concepts for ecological engineering, that is, landscape-level management of insect pests, will restore and sustain vital ecosystem services that rely on greater biodiversity.

Wider adoption of all these promising technologies will require strong policy support. Instead of investing in subsidizing inputs (as perceived quick fixes), governments should shift their policies toward greater support for the adoption of sustainable, eco-efficient management practices. Moreover, finding ways to include smallholder rice farmers in international, national, or local payment for environmental services schemes (e.g., clean development mechanisms for carbon trading and others) would greatly enhance the adoption of more environment-friendly management practices, provided there is no income penalty or increased risk. Such technologies will only spread wide and far if yields are high enough to ensure food security and better incomes for farmers.

Adding value. Current processing practices in the developing world cause around 15–25% physical loss and, because of poor quality, financial loss at the market of 10–20%. Many new technologies exist to reduce such postharvest losses (Chapter 2.6), but they will require significantly increased investments for achieving wider impact. They also provide excellent opportunities for public-private partnerships.

Demand for specialty products from rice is increasing globally and more research is needed in that area and on the use of rice by-products. New scientific opportunities are emerging to systematically breed high-quality rice for top-end market segments, but also enhancing the nutritional value of rice, or improving processing technologies. Although much of the latter will take place in the private sector, public-sector research has a role to play, particularly in breeding for new quality traits and in finding ways to enable smallholder farmers to capture more value. Each year, hundreds of millions of tons of rice straw and husks are produced and largely disposed of by burning. Innovative uses, such as bioenergy and biochar from rice husks and straw, will provide local business opportunities and extra income sources for farmers, and simultaneously mitigate, instead of accelerate, climate change. Another option is to improve the digestibility of the straw so that it can be used more widely as livestock feed.

Policies and institutions

Trade and markets. For a variety of reasons, governments intervene in rice markets and trade more than for any other agricultural commodity. Interventions date from a time when rice trade was very thin and countries lacked infrastructure and the reserves to depend on trade. In most of Asia, these circumstances have changed, yet interventions through various parastatal agencies and high tariff protection remain common. These interventions create inefficiencies such as a lack of incentives to diversify in irrigated areas. Some of these interventions stabilize domestic prices but at the expense of international price volatility. The richer Asia of today is in a much better position to deepen trade and liberalize rice markets. In most cases, lower protection would benefit the poor, who are net purchasers of rice. A reduction in subsidies to water and agro-chemicals would also provide incentives needed to use water and inputs more efficiently and to adopt agroecological approaches to rice farming.

Yet, global rice markets are still thin relative to other cereals and therefore inherently more volatile (Dorosh and Wailes, Chapter 3.1). In addition, the 2008 export bans and stockpiling have seriously undermined confidence in rice trade. This suggests that a gradual and sequential approach to market liberalization is needed that encourages private trade, the use of trade to reduce price volatility to consumers when there is a domestic shock (as in Bangladesh in 1998—Dawe et al, Chapter 3.2), and the deployment of "light-touch" interventions to reduce the domestic effects of extreme price events in global markets. Minimal emergency reserves and variable tariffs if implemented in a transparent and rule-based manner could go a long way to restoring confidence in trade and encouraging private markets and storage. Interventions should also be designed so that domestic prices track medium-term trends in world markets in order to reduce inefficiencies in resource allocation when domestic and international prices are significantly misaligned. Scaled-up safety net programs that are countercyclical to price shocks and well targeted to the most vulnerable are needed to provide more tolerance for domestic price movements.

Other proposals are on the table to improve the functioning of global markets, such as global grain reserves or virtual reserves (Chapter 3.2). However, the estimated costs ($12 to $20 billion for a virtual grain reserve) will at best mean that adoption of these measures will take time.

Institutional change. The importance of institutional change as a core element of sustainable rice systems and effective markets permeates almost all chapters of this book. Given water scarcity, new institutional designs to better manage and coordinate irrigation are the major focus of Chapter 2.4. This involves institutions to better coordinate cross-sectoral water allocation, collective action to manage irrigation systems, and better defined water rights, although the exact institutional mix will need to fit local circumstances. Likewise, farm consolidation to facilitate exit from rice farming requires well-functioning land markets, both for rental and for sale (Chapter 2.1). Restrictions on land sales in a number of countries are likely to be major barriers to shedding labor from rice farming as the nonfarm sector expands.

Production systems that reduce input use require institutional changes on several fronts. Public extension is increasingly being complemented or even supplanted by a range of providers of advisory services, radio and drama programs, and technical and market information delivered through village kiosks and mobile devices. Tapping the large potential of genetically modified organisms (GMOs) requires a strong but decisive regulatory capacity to ensure that farmers have timely access to the best technologies. Institutional strengthening is needed to preserve the free use and exchange of genetic resources across countries, while providing incentives to the private sector through intellectual property rights appropriate to the stage of seed market development (Chapter 2.2).

Finally, markets for high-value crops and livestock are developing rapidly throughout Asia, but small farmers often face obstacles in linking to demanding markets in terms of quality and safety. Investing in education, skills, rural infrastructure, and communications is key to the development of a dynamic nonfarm sector (Chapters 1.2 and 1.3).

Investing in R&D for the future

Some countries, especially China, India, and Brazil, have recognized the critical importance of investing in science and technology for the future and are rapidly scaling up their investments. Yet, rice science globally is characterized by pervasive underinvestment as demonstrated by the analysis of high payoffs in Beintema et al (Chapter 4.3). Indeed, there is a growing divide between the few countries that are scaling up R&D investments and the rest. The need for sustained long-run investment is nowhere more evident than in sub-Saharan Africa, which has to make up for decades of neglect. Revamping national rice research systems, however, requires more than funding, since human resource capacity has been sharply eroded by retirement and a lack of investment in higher university education. A global effort to rebuild capacity in rice science should be at the top of the priorities.

The private sector is poised to play an ever greater role in rice research, as hybrids, plant varietal protection, and GMOs carrying patents become more widely established. The growing complexity of science, the rise of the private sector, and the emerging scientific strength of the BRIC (Brazil, Russia, India, and China) provides new opportunities for partnerships. Making these partnerships function effectively will be crucial to meeting the major challenges facing the world rice economy in the coming decades. Spearheaded by three Consultative Group on International Agricultural Research (CGIAR) centers, IRRI, AfricaRice, and the International Center for Tropical Agriculture (CIAT), rice researchers are entering an exciting new Global Rice Science Partnership (GRiSP) that will harness the best of science and development to address the "mega-challenges" facing the global rice economy.

THEME 1:

Rice in the global food economy

Emerging trends and spatial patterns of rice production

David Dawe, Sushil Pandey, and Andrew Nelson

Introduction

Rice is one of the most widely grown crops in the world, and it is the most important food crop for the poor. This introductory chapter provides some basic background facts and analysis on the location and importance of global rice production and consumption, the biophysical nature of rice production systems, and historical trends in area, yield, and production.

Rice (*Oryza sativa*) was probably first domesticated in the Yangtze River Valley in China (Vaughan et al 2008), perhaps about 7,000 years ago, after which it spread to other parts of Asia. Much later, it spread to Europe, possibly through Alexander the Great's expedition to India in the 4th century BC. Portuguese and Spanish colonists then introduced it to Latin America. The first record of cultivation in North America is 1685 in what is now South Carolina—it may have been carried to that area by African slaves (Maclean et al 2002). A different species of rice, *O. glaberrima*, was domesticated separately from *O. sativa* in the basin of the Upper Niger River in western Africa.

Global rice production and consumption

Wheat, rice, and maize are the three most widely grown crops in the world. According to Portmann et al (2010), global harvested area around 2000 was approximately 215 million ha for wheat, 166 million ha for rice, and 152 million ha for maize (harvested area includes estimates of multiple cropping and is different from land area).[1,2] Wheat has had the largest area harvested for many decades, but there has been no trend increase in its area during the past 50 years. Rice and especially maize area have been increasing and, in 2007 and 2008, maize area harvested was greater than that of rice. Although global rice area harvested increased 33% between 1961 and 1975 (1.48% per year), it increased only a further 12% (0.35% per year) between 1975 and 2008 (raw data from FAO 2010a).

Although rice farming is important to particular regions in some developed countries, it is of much greater importance to low- and lower-middle-income countries, where it accounts for 19% of total crop area harvested. In upper-middle- and high-

[1]For example, if a single hectare of land grows two crops of rice per year, this hectare of land counts as 2 ha of harvested area.

[2]Estimates from FAO and USDA are similar, although the estimates of harvested area in Portmann et al (2010) are about 9−10% higher than in the other two sources for rice and maize.

income countries, it accounts for just 2% of total crop area harvested. We estimate that, in the first half of the 2000s, there were approximately 144 million rice farm households in the world, the vast majority in developing countries (see Appendix for details of calculation). Although we have not done calculations for the number of wheat or maize farm households, the number of such farm households is likely to be much less than the number of rice farm households, as large shares of wheat and maize area are in upper-middle-income and developed countries, where farm sizes are larger. Specifically, in 2008, 94% of total rice area was in low- and lower-middle-income countries compared with just 52% for maize and 41% for wheat.

Of the three major crops, rice is by far the most important in terms of human consumption in low- and lower-middle-income countries (Table 1). Maize has been primarily a feed crop—USDA (2010) estimates that feed use has historically accounted for about two-thirds of total consumption. This proportion has declined slightly in recent years to about 60%, but this is due to increased biofuel demand, not increased human consumption. For wheat, about one-fifth of production is typically used as animal feed. Of the remaining four-fifths, a large share is consumed in developed countries. In the case of rice, on the other hand, very little is used for feed, and rice consumption is relatively low in Europe and the United States.

Even though rice is the dominant food crop for low- and lower-middle-income countries, Table 1 still understates its importance to the poor because much of the wheat consumption in low- and lower-middle-income countries of Asia is restricted to the upper parts of the income distribution. Table 2 shows the proportions of rice and wheat consumption by the poorest and richest 20% of the population in a few large low-income countries in Asia for which data were easily available. These data show that, although rice consumption is spread across income classes relatively equally in these countries, the poorest people actually consume relatively little wheat—most of the wheat consumption is done by people in the upper part of the income distribution (who are not below the poverty line). The reverse does not appear to be true in areas where wheat is the staple food, for example, Pakistan and the wheat-eating provinces in China.[3] Thus, rice is clearly a very important food crop for the poor.

Regional rice production and consumption

Although rice is grown worldwide (Hijmans 2007), world rice production and consumption are dominated by that part of Asia from Pakistan in the west to Japan in the east. "Rice-producing Asia" as thus defined (excluding Mongolia and the countries of Central Asia) accounted for 90% of world rice production, on average, from 2006 to 2008, little changed from the 91% between 1961 and 1963. Because rice-producing Asia is a net exporter of rice to the rest of the world, its current share in global rice consumption is slightly less, at about 87%.

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[3]In Pakistan, per capita rice consumption is relatively equal across income groups (FBS 2001). In the 13 provinces in China where wheat is the main staple (Beijing, Gansu, Hebei, Henan, Inner Mongolia, Ningxia, Qinghai, Shaanxi, Shandong, Shanxi, Tianjin, Tibet, Xinjiang), the ratio of rice consumption in the top quintile to rice consumption in the bottom quintile is just 1.6 (raw data from Timmer et al, this volume), much less than the ratios for wheat in Indonesia, Bangladesh, and the Philippines shown in Table 2.

Table 1. Percentage of calories supplied by various staple foods, 2005.

Country group	Rice	Wheat	Maize	Roots and tubers	Other cereals
Low and lower middle income	27	18	5	6	4
Sub-Saharan Africa	8	8	15	20	15
Rice-producing Asia	33	18	3	4	2
Other	7	35	9	4	2
Upper middle and high income	6	20	6	4	1
All countries	20	19	5	6	3

Source of raw data: FAO (2010a). Accessed 19 April 2010. The low- and lower-middle-income countries in rice-producing Asia are Bangladesh, Cambodia, China, India, Indonesia, DPR Korea, Lao PDR, Maldives, Myanmar, Nepal, Pakistan, Philippines, Sri Lanka, Thailand, Timor-Leste, and Vietnam.

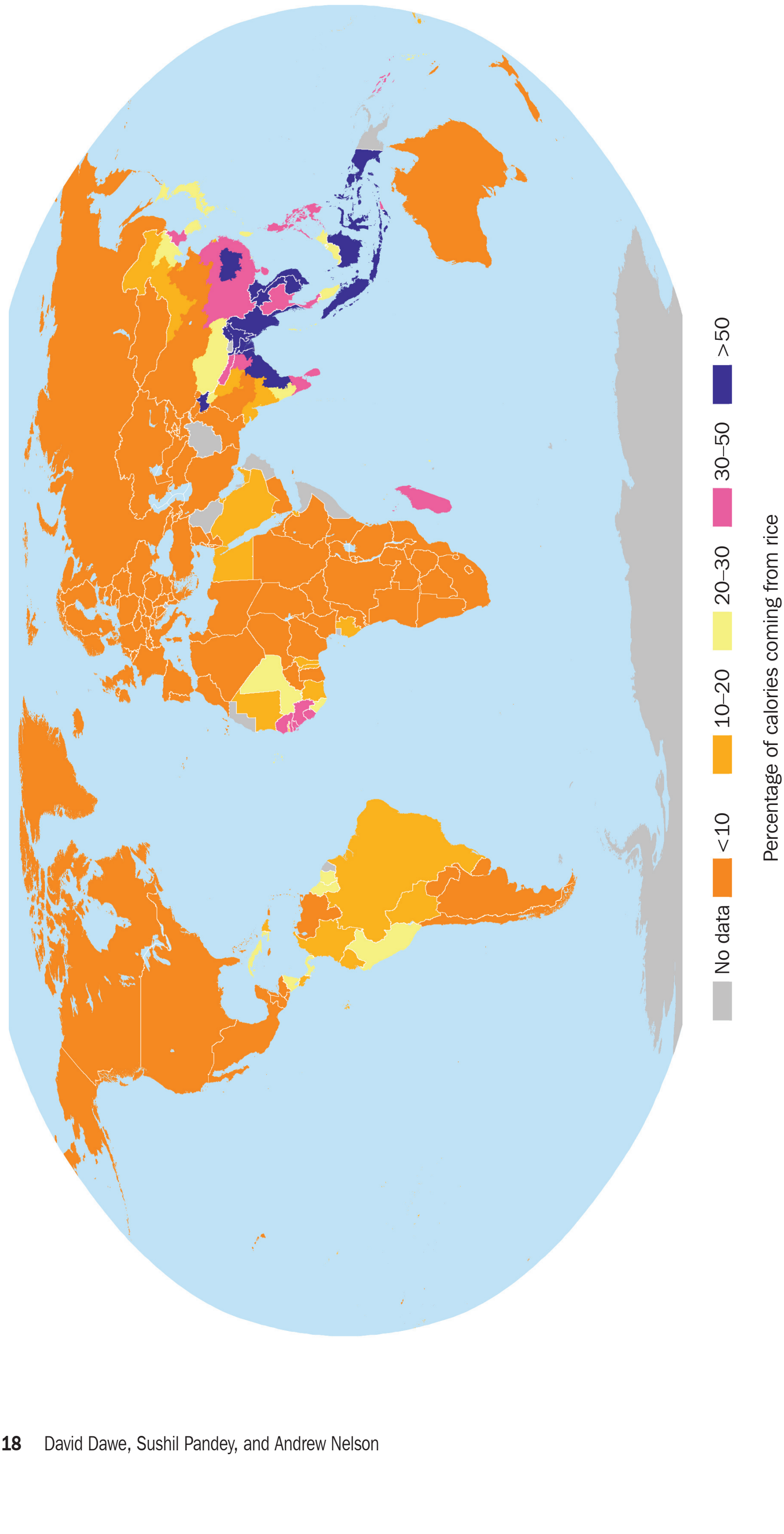
Table 2. Percentage of national rice and wheat consumption by the poorest and richest quintiles of the population.[a]

Country (survey year)	Rice		Wheat	
	Poorest	Richest	Poorest	Richest
Bangladesh (2005)	18	21	9	45
Indonesia (1999)	17	19	6	43
Philippines (1999-2000)	18	22	15	27

[a]Percentages are calculated on the basis of consumption quantities (kg), not value. Sources of data: BBS (2007) for Bangladesh, BPS (2000) for Indonesia, and BAS (2001) for the Philippines.

Rice also dominates overall crop production (as measured by the share of crop area harvested of rice) and overall food consumption (as measured by the share of rice in total caloric intake) to a much greater extent in rice-producing Asia than elsewhere in the world. On the consumption side (Map 1), the only countries outside Asia where rice contributes more than 30% of caloric intake are Madagascar, Sierra Leone, Guinea, Guinea-Bissau, and Senegal (countries with population less than 1 million are excluded). On the production side (Map 2), the only countries outside Asia where rice accounts for more than 30% of total crop area harvested are Madagascar, Sierra Leone, and Liberia in West Africa, plus Suriname, Guyana, French Guiana, and Panama in Latin America.

Within Asia, the largest producers by far are China and India. Although its area harvested is lower than India's, China's rice production is greater due to higher yields (due in turn to a much greater proportion of irrigated area—nearly all of China's rice area is irrigated, whereas less than half of India's rice area is irrigated). After China and India, the next largest rice producers are Indonesia, Bangladesh, Vietnam, Myanmar, and Thailand (Fig. 1). These seven countries all had average production in 2006-08 of more than 30 million tons of rough rice. The next highest country on the list, the Philippines, produced only a little more than half that. Collectively, the top seven countries account for more than 80% of world production.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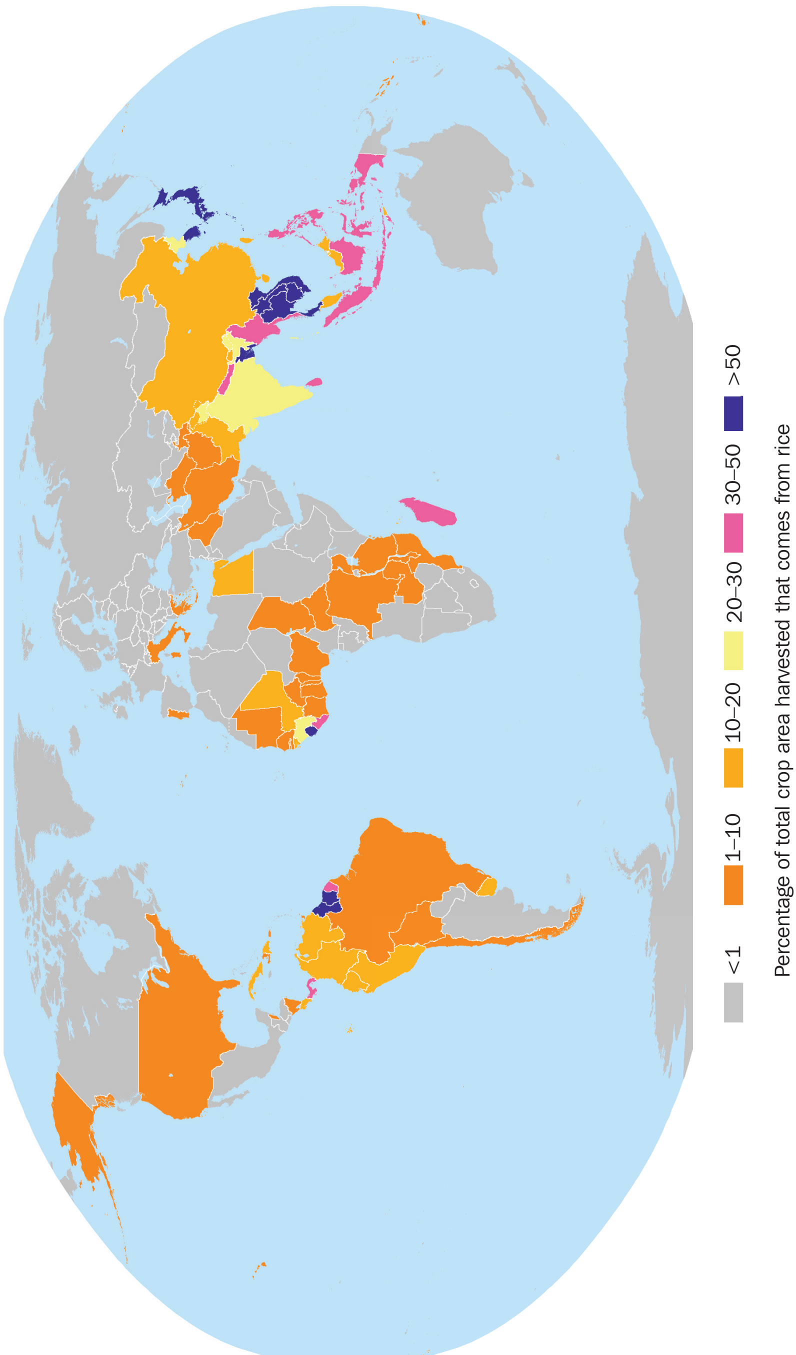
Percentage of calories coming from rice

Map 1



<1
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Percentage of total crop area harvested that comes from rice

Map 2

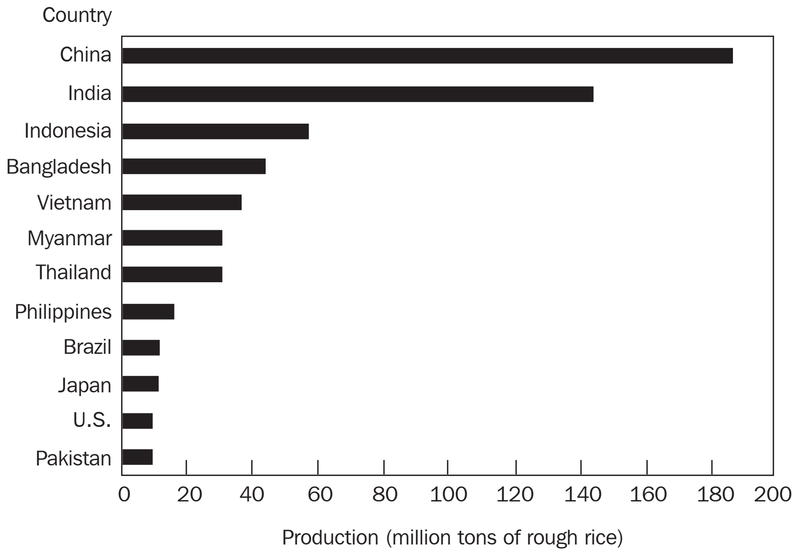

Fig. 1. Leading rice producers in the world, 2006-08.

Despite Asia's dominance in rice production and consumption, rice is also very important in other parts of the world. In Africa, for example, rice is the main traditional staple food (defined as the food, among those listed in Table 1, that supplies the largest amount of calories) in parts of western Africa (Guinea, Guinea-Bissau, Liberia, Sierra Leone). In these countries, the share of calories from rice has generally not increased substantially over time. In other African countries, however, rice has displaced other staple foods because of the availability of affordable imports from Asia and rice's easier preparation, which is especially important in urban areas. In Côte d'Ivoire, for instance, the share of calories from rice increased from 12% in 1961 to 22% in 2007. In Senegal, the share increased from 20% to 31% during the same time, whereas, in Nigeria, the most populous country on the continent, it increased from 1% to 8%. On balance, in Africa, production has grown rapidly, but rice consumption has grown even faster, with the balance being met by increasing quantities of imports. Western Africa is the main producing subregion, accounting for more than 40% of African production in 2006-08. In terms of individual countries, the leading producers of rough rice (2006-08) are Egypt (7.0 million tons), Nigeria (3.8 million tons), and Madagascar (3.2 million tons).

In Latin America and the Caribbean, rice was a traditional crop in some countries of the Caribbean and a preferred pioneer crop in the first half of the 20th century in the frontiers of the Brazilian Cerrado, the savannas of Colombia, Venezuela, and Bolivia, and in forest margins throughout the region (IRRI 1997). Today, rice is the most important source of calories in many Latin American countries, including Ecuador and Peru, Costa Rica and Panama, Guyana and Suriname, and the Caribbean nations of Cuba, the Dominican Republic, and Haiti. It is less dominant in consumption than in Asia, however, because of the importance of wheat and maize in regional diets. Brazil is by far the largest producer, and it accounts for nearly half (46% in 2006-08) of rough rice production in the region. After Brazil (11.6 million tons), the largest producers are Peru and Colombia (2.5 million tons each in 2006-08), followed by Ecuador (1.6 million tons).

Outside of these areas, the most important production centers (California and the southern states near the Mississippi River) are in the United States, which produced 9.0 million tons of rough rice on average from 2006 to 2008. The leading European producers are Italy, Spain, and Russia. Australia used to be an important producer, but its output has declined substantially in recent years because of recurring drought.

Characteristics of rice production systems

Farm size

Rice is grown on both small and large farms (see Table 3 for data on average rice farm size for all countries for which data are available from FAO 2010b). Rice farms are generally smallest in Asia and Africa. In both regions, farms are often less than 1 ha in size. In Latin America, rice farms tend to be larger, but typically less than 5 ha (Uruguay is a notable exception). In Europe, average rice farm sizes range from 3.9 ha in Greece to 40.6 ha in Italy. Finally, in the United States (and in Uruguay), the average rice farm size is well over 100 ha. However, many important countries are not listed

Table 3. Average rice farm size, various countries.[a]

Country/region (year)	Rice farm size (ha)	Country/region (year)	Rice farm size (ha)
Asia		**Americas**	
Iran (2003)	0.90	Brazil (1996)	3.21
Japan (2000)	0.84	Ecuador (2000)	4.54
Malaysia (2005)	1.32	Panama (2001)	2.31
Pakistan (2000)	1.81	Uruguay (2000)	276.60
Philippines (2002)	1.82	U.S. (2002)	160.83
Thailand (1993)	2.60		
Africa		**Europe**	
Egypt (2000)	0.61	Greece (1995)	3.94
Ethiopia (2001)	0.28	Italy (2000)	40.59
Gambia (2001)	0.32	Portugal (1999)	11.52
Guinea (1995)	1.37	Spain (1999)	9.42
Tanzania (2003)	0.71		
Zambia (1990)	0.72		

[a]The table shows all countries for which data are available in the World Census of Agriculture (FAO 2010b). The years in parentheses refer to the year of census. Rice farm size is defined as the physical farm area available for growing rice.

in Table 3, and there can be a great deal of heterogeneity within regions. Indeed, there is also a great deal of heterogeneity within countries. In Brazil, for example, while a national average of 3.2 ha was reported in 1996, rice farms in the province of Rio Grande do Sul are similar in size to those in neighboring Uruguay (IRGA 2010).

Water source

Rice production systems can be characterized in many ways, but clearly one of the most important is based on water source. Irrigated rice is rice grown using water supplies that supplement rainfall and natural runoff, for example, water from large-scale human-made surface irrigation systems or groundwater. Use of these additional supplies, coupled with good drainage, gives greater control over the level of water in the field and provides favorable growing conditions for rice.

Rainfed rice is rice grown using only rainfall and natural runoff, and these systems are more heterogeneous than irrigated rice systems. Within the category of rainfed rice, several distinct systems present different management challenges: rainfed lowland, upland/dryland, and deepwater. Rainfed lowland rice is grown using bunds that store water within the field, which creates an anaerobic growing environment that is similar to that for irrigated rice. Upland/dryland rice is grown without such bunds, so that the crop is grown under aerobic conditions, similar to those for field crops such as wheat and maize. Deepwater rice is rice that is subject to substantial floods that can submerge the crop to depths of 1 meter or more.

The greater water control that exists in irrigated rice systems reduces many (not all) of the risks associated with farming, in particular the risk of drought. As a result, rice farmers with irrigated land typically apply more fertilizer and get higher yields than do farmers with rainfed land. In the Philippines in 2008 and 2009, for example, irrigated rice yields were about 55% higher than rainfed rice yields. For Asia as a whole in 2005, the average yield of irrigated rice was about 50% higher than yield in rainfed areas (Hossain 2006).

Rice has a greater area irrigated than any other crop in the world, at more than 100 million ha in 2000 (wheat is second at 67 million ha), and it accounts for about one-third of the world's total irrigated area harvested. Among the three major cereals, the percentage of area irrigated is 62% for rice, 31% for wheat, and 20% for maize (Portmann et al 2010).

The proportion of rice area that is irrigated has been increasing over time. The most important reason for this increase has been the expansion of irrigation through both public investments (for surface irrigation) and private investments (for groundwater irrigation). Government and donor investment in large surface irrigation systems (often coupled with dams) was particularly pronounced in the 1970s and 1980s, but that investment has subsequently declined substantially. More recently, groundwater irrigation has become more important, much of it driven by private investment.

Between the late 1970s and the mid-1990s, dry-season irrigated area in Asia[4] increased by 6.2 million ha, out of a total increase in rice area of 5.9 million ha (Huke and Huke 1997).[5] Wet-season irrigated area also increased by 2.2 million ha. Some of the increase in wet-season irrigated area was most likely due to the conversion of rainfed land, although a lack of plot by plot data prevents a firm answer to this question (i.e., the increase in wet-season irrigated area could have also been due to opening of new land).

These increases in irrigated area are even larger outside of China, because rice area declined in China when farmers were allowed more choices under the reforms that began in 1978 (and nearly all rice land in China and the rest of East Asia is irrigated). Excluding China, dry- and wet-season irrigated area increased by 6.7 and 5.7 million ha, respectively.[6] The increases in irrigated area were spread across a number of countries, including all of the major rice-growing countries/regions with the exception of Japan, the Republic of Korea, and Taiwan.

In addition to the large increase in irrigated area, large areas of upland (3 million ha) and deepwater rice (1.2 million ha) in Asia were converted to other crops (and thus lost to rice) between the late 1970s and the early to mid-1990s, constituting a 25% decline in the rice area in these ecosystems (Huke and Huke 1997). Combined, this amounted to a decline of 4.2 million ha. Declines in the rice area in these ecosystems appear to have continued since that time, and have occurred outside of Asia as well. In Brazil, for example, the area of upland rice increased during the 1960s and 1970s in response to land concessions and government subsidies for land expansion. Since the peak was reached, however, the area of upland rice has declined by about two-thirds (Fig. 2).

Thus, while irrigated area comprised about 51% of total rice area in the late 1970s in Asia, it accounted for 55% of total rice area in the early to mid-1990s and 57% in the first decade of the 21st century.[7] In South and Southeast Asia (i.e., excluding East Asia), the relative increase in irrigated area has been more significant, rising from just 33% of total area in the late 1970s to 43% in the early to mid-1990s and to 46% in the first decade of this century.

Within Africa, irrigated systems are much less common than in Asia. Irrigated systems account for only 20% of total rice area in Africa (Balasubramanian et al 2007), while the corresponding figure in Asia is 57%. Indeed, this is one of the major reasons for lower average rice yields in Africa. A comparison of average rice yields in Asia and Africa ecosystem by ecosystem shows only small differences (IRRI 1997,

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[4] Comparable data over time are not available for other parts of the world, at least not to our knowledge.

[5] The increase in dry-season irrigated area is greater than the increase in total area because the area in other ecosystems (e.g., rainfed, upland) declined.

[6]This statement refers to data collected by Huke and Huke (1997) covering the period between the late 1970s and the mid-1990s.

[7] It is possible, perhaps even likely, that these figures overstate the increase in the share of irrigated area because official statistics may not accurately reflect the deterioration of irrigation systems that has taken place in many areas after the Green Revolution led to falling world rice prices. However, it is hard to estimate the magnitude of this effect. The most recent data are work in progress and will be revised as better data become available.

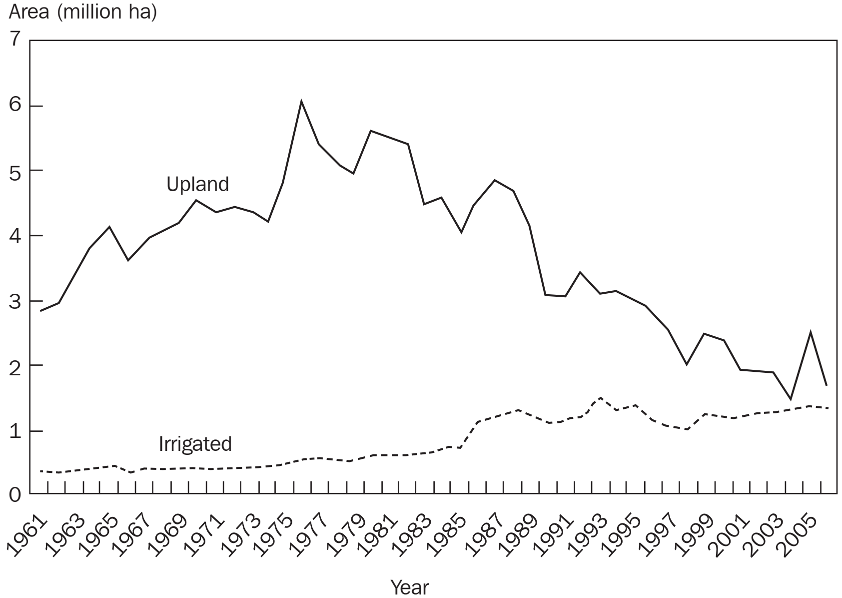

Fig. 2. Rice area by ecosystem in Brazil, 1961-2006. Data source: Gonzalo Zorrilla of the Latin American Fund for Irrigated Rice (FLAR).

p 181), but in aggregate average yields in Asia are much higher because of the greater importance of the higher-yielding irrigated ecosystem. The most extensive rice ecosystems in Africa are dryland rice (38% of total rice area) and rainfed wetland rice (33%), with deepwater and mangrove rice accounting for the remaining 9% of rice area. It is especially challenging to achieve high yields in dryland, deepwater, and mangrove rice systems. In Latin America, upland rice systems constitute the largest share of rice area, although this proportion has declined substantially over time. The most recent figures suggest that about 46% of rice area is under upland systems, 37% is irrigated, and 16% is rainfed lowland. Because of higher yields with irrigation, irrigated systems are estimated to account for 59% of production (IRGA 2010).

Multiple cropping

Not surprisingly, irrigated systems tend to grow more crops of rice (and more crops in general) per year than rainfed systems: 48% of irrigated systems grow more than one crop of rice, while this is true for only 27% of rainfed systems (Table 4). Within irrigated systems, a relatively even distribution of area occurs across the four cropping systems. Rice-fallow, rice-other, and multiple-crop rice-only systems (either two or three rice crops per year) each total about 21 million ha, while rice-rice-other systems total 17.2 million ha. Regional differences are large, with the more intensive double and triple rice-cropping systems dominating in the more humid and tropical areas of Southeast and East Asia and single rice-cropping systems (such as the vast rice-wheat area of the Indo-Gangetic Plains) dominating in South Asia.

Table 4. Rice area (million ha) by cropping system and water source for Asian regions, 2000-09.

Cropping system	South Asia	Southeast Asia	East Asia	Total
Irrigated	30.6	19.6	30.7	80.8
Rice-fallow	9.5	0.8	10.2	20.6
Rice-other	13.9	1.7	5.7	21.3
Rice-rice or rice-rice-rice	5.7	10.5	5.6	21.8
Rice-rice-other	1.4	6.5	9.2	17.2
Rainfed	30.7	27.3	2.3	60.3
Rice-fallow	21.1	11.0	2.3	34.4
Rice-other	4.2	5.7	0.0	9.9
Rice-rice	5.4	10.6	–	16.0
Grand total	61.3	46.9	33.0	141.2

Sources of data: compiled by IRRI from IRRI (2010), Huke and Huke (1997), Hijmans (2007), FAO (2002), Maclean et al (2002), Portmann et al (2008), Frolking et al (2002, 2006), and Gumma et al (forthcoming).

The rice-fallow cropping system dominates rainfed areas and is larger than the rice-other and double-rice systems combined (34.4 million ha compared with a total of 26.0 million ha for the latter two systems). The majority of the rice-fallow rainfed area is in South Asia, and it dominates the rainfed rice area in this part of the world. Southeast Asia has a more even distribution of cropping systems in rainfed areas, with 40% of its total rice area under rice-fallow, 21% under rice-other, and 39% under double rice. East Asia has very little rainfed area.

Variations in yield and area harvested across countries

As noted above, irrigated rice outyields rainfed or upland rice. However, some biophysical factors affect rice yields other than water control, of which the length of the cropping season and the availability of sunlight are the most important. Rice that is grown in temperate climates tends to have a longer growth duration (i.e., the number of days between crop establishment and harvest), and also tends to receive more sunlight per day because of the longer daylengths at higher latitudes. These two factors mean that crops in temperate climates receive more total photosynthetic radiation, which typically leads to higher yields.

Provided there is irrigation water, arid areas also tend to have a yield advantage because the lack of cloud cover increases the sunlight available for photosynthesis. These factors can explain much of the variation in rice yields across countries and why rice yields tend to be higher in temperate climates than in tropical environments. For example, average rice yields in Egypt, where rice is grown with irrigation water from the Nile under arid conditions, were about 9.9 t/ha on average from 2006 to 2008 (FAO 2010a). In Malaysia, by contrast, yields averaged 3.5 t/ha during the same period. It is of course possible that some of this yield differential is due to differences in farmer skills, but the bulk of the difference is due to different biophysical growing conditions, many of which cannot be changed.

Although rice yields (per unit area harvested) in temperate countries tend to be higher than in tropical countries, there is sometimes a greater potential for rice area harvested in the tropics because growing seasons (i.e., the number of days per year when temperatures allow crops to be grown) are longer and there is thus potential for double and triple cropping (growing two or three crops per year). Double cropping is very common in the tropics, and in some areas with ample supplies of water (e.g., the Mekong Delta, the Central Plain of Thailand), many farmers plant three crops of rice per year. Such practices are not possible in more temperate climates because the cold winters preclude a second rice crop. If rice yields are considered per unit of physical area instead of per unit of harvested area, then annual yields in some areas of the tropics exceed those in temperate climates. In other words, annual production potential may be higher in the tropics, even if per crop yield potential is higher in temperate climates.

There is also variation in rice area harvested across countries due to water availability. Given that a much larger share of rice area is irrigated than for other crops, it is not surprising that much rice production takes place around some of the world's major river basins (China—Yangtze and Pearl rivers; India and Bangladesh—Ganges and Brahmaputra; Pakistan—Indus; Cambodia and Vietnam—Mekong; Mali and Nigeria—Niger; Egypt—Nile; the U.S.—Mississippi; Italy—Po). Of course, rice production is not restricted exclusively to areas with long rivers, but there is certainly a correlation between the two.

Production, area, and yield trends over time

Global rice production more than tripled between 1961 and 2008, with a compound growth rate of 2.49% per year (2.45% in rice-producing Asia).[8] This increase was slightly greater than that for wheat (2.44% per year), but substantially less than that for maize, which grew at 3.00% per year. Most of the increase in rice production was due to higher yields, which increased at an annual average rate of 1.79%, compared with an annual average growth rate of 0.68% for area harvested. In absolute terms, rough rice yields increased at an annual average rate of 51.9 kg/ha per year, although this rate of increase has declined in both percentage and absolute terms.

[8]We have chosen to do much of the analysis in this chapter in percentage terms rather than in absolute terms (e.g., kg per ha per year), although we do also report some trends in absolute terms. Our objective is to compare production growth with demand growth because production is not done for its own sake, but rather to feed people. Because population growth is the main driver of demand growth for rice, and because population growth is an inherently exponential (i.e., percentage) process, demand tends to increase a certain percentage per year, as opposed to a certain number of kilograms per year. Thus, we think it is illuminating to calculate production growth in percentage terms.

Since most rice is produced and consumed in rice-producing Asia, it makes sense to compare these growth rates with population growth in that part of the world. Population growth in this region was 1.79% per year from 1961 to 2008, nearly identical to the rate of yield growth. Coupled with the expansion in area harvested, this yield growth led to a cumulative 36% increase in per capita production during the period.

The trend in rice yield has been positive in all parts of the world although the rates of growth and yield vary by region (Fig. 3). Yields are much higher in East Asia and the U.S. than in most of the rest of the world. After an initial rapid growth in yield in East Asia, the yield growth rate has decreased considerably, with the yield trend being almost flat during recent years. On the other hand, yield has continued to grow in the U.S. despite some fluctuations. The average yields in recent years are now almost 20% higher than in East Asia.

The yield trends for South and Southeast Asia are similar to that of East Asia, but yields are lower. These regions have substantial area under rainfed conditions, in contrast with East Asia, where rice is grown mainly under irrigated conditions. Growth in yield has fallen over time in both South and Southeast Asia, especially after the mid-1990s. Africa is the region with the lowest average yield due to largely rainfed area. In addition, the historical growth rate in yield has also been lower, although there is some indication of an increase in growth rate during more recent years.

Changes in rice area harvested: extensification or intensification?

National and global production statistics typically report area harvested, not physical area. If a farmer plants two crops of rice, each of 4 months' duration, on 1 ha of land in a given year, then the physical rice area would be 1 ha, but rice area harvested would be 2 ha. Growth in area harvested can thus come from either expansion of the physical

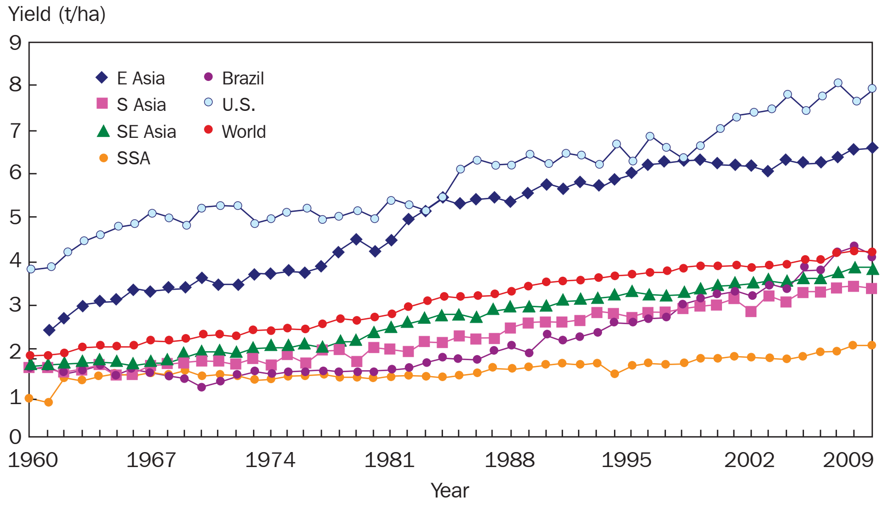

Fig. 3. Trends in rough rice yield in different regions of the world.

area given to rice or an increased cropping intensity, for example, growing two crops of rice per year on 1 ha of land when only one crop was grown before.

Data on the relative magnitude of increases in physical area and rice-cropping intensity are typically not available in most countries. Some countries, however, have data available on rice area harvested by season. In order to exploit these data, we make the reasonable assumption that all farmers who plant rice in secondary seasons (e.g., the dry season) plant that same land to rice in the main season (e.g., the wet season). The change in physical area over time is then given by the change in the maximum seasonal area harvested to rice, where the maximum is taken across seasons for each year. The change in cropping intensity is then the total change in area harvested minus the change in physical area.

Columns (1) and (2) of Table 5 show the percentage increase in physical area for rice and the percentage change in rice-cropping intensity for a small sample of countries for which we could obtain data on rice area harvested by season. Combined, these two factors account for the increase in area harvested.

In Bangladesh and Vietnam, two countries with high population densities, there has been a small contraction in the physical area planted to rice, while increased cropping intensity has more than compensated for that loss. In India, the Philippines, and Sri Lanka, there has been a net increase over time in both physical area and cropping intensity, with the increase in cropping intensity being equal to or larger than the increase in physical area. Finally, in Thailand and Lao PDR, two countries with relatively low population densities by regional standards, the increase in physical area has surpassed the increase in cropping intensity by a fair margin.

Yield growth due to area shifts

Just as the growth in area harvested can be broken down into changes in physical area and cropping intensity, growth in yield also has two components: growth in yield within a specific ecosystem (e.g., irrigated or rainfed) or season, and growth in yield due to area shifts from one ecosystem or season to another (columns (3) and (4) of Table 5). In all countries, within-ecosystem yield growth (weighted average yield growth across ecosystems/seasons, with initial period allocations as weights) has been the dominant source of yield growth, with yield growth due to shifts in area across ecosystems being generally low. Among all the countries listed in Table 5, Bangladesh has experienced the most yield growth due to area shifts. This has come from an increased dominance of irrigated boro-season rice (the area quadrupled between the early 1970s and the last few years of the 2000s) at the expense of upland rice grown in the aus season, in which area harvested declined by 69%. But, even in Bangladesh, most of the yield growth was due to growth within ecosystems/seasons, not area shifts across ecosystems.

The recent slowdown in rice area and yield growth

In recent years, growth in both area harvested and yield has slowed down relative to what it was in earlier periods. Although global rice area harvested increased by 1.38% per year between 1961 and 1977, the rate since then has been just 0.33% per year.

Table 5. Annual percentage increase in rice production due to increases in various factors.

Country (years)	Physical area (1)	Cropping intensity (2)	Yield growth[a] within ecosystems (3)	Area shifts across ecosystems (4)
Bangladesh (1970-71–2008-09)	–0.08	0.38	1.92	0.74
India (1962-2007)	0.20	0.17	1.34	0.08
Indonesia (1968-2009)	–	–	2.02	0.13
Lao PDR (1976-2008)	1.00	0.37	2.73	0.57
Philippines (1970-2009)	0.27	0.57	2.08	0.21
Sri Lanka (1979-2009)	0.02	0.44	1.46	0.00
Thailand (1956-2007)	0.94	0.39	1.16	0.18
Vietnam (1976-2008)	–0.13	1.14	2.99	0.16

[a]Growth rates are compound annual average growth rates, using an average of the first and last three years of the periods indicated as endpoints. For Indonesia, data by season were not available, so there are no calculations reported in columns (1) and (2).
Source of raw data: IRRI (2010).

Yield growth has also slowed substantially, in both percentage and absolute terms.[9] Although rice yields are still growing, the rate of growth has been declining steadily for many years (Fig. 4). Fortunately, population growth in rice-producing Asia has been steadily declining for even longer. Since population growth has been the main source of rice demand growth, this trend helped to keep rice prices in check for a time. But, since the mid-1990s, population growth has exceeded rice yield growth and the gap has been growing steadily larger, creating a significant imbalance between supply and demand. This trend is evident for Asia as a whole, but also separately for East Asia, Southeast Asia, and South Asia. Stagnation in area harvested further contributed to the problem, and prices eventually began to rise. Indeed, world market rice prices rose steadily by a cumulative 67% between April 2001 and September 2007, even before the world rice crisis.

Changes in rice production variability over time

Despite some initial concerns, growth in rice production in the wake of the Green Revolution was generally accompanied by a long-term decline in production variability. The coefficient of variation (CV) of production, estimated using linearly de-trended data for rolling 10-year periods, generally decreased over time globally and across all regions (Fig. 5).

[9]A regression of world rice yield (kg/ha) on linear and quadratic time trends gives a negative and statistically significant coefficient on the quadratic term. Thus, the rate of increase in rice yields has been slowing, even in absolute terms (Fischer et al 2009).

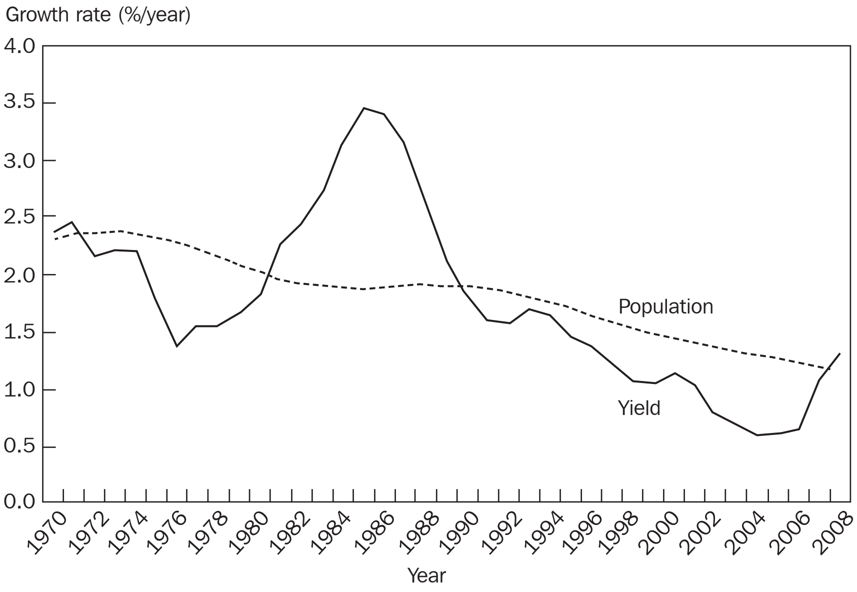

Fig. 4. Annual average percentage increase in rice yields and population between successive rolling 5-year periods in rice-producing Asia. The figure shows the annual average percentage change in yields and population. For example, the data for 1970 are the percentage change between 1966-70 and 1961-65. Source of raw data: FAO (2010a).

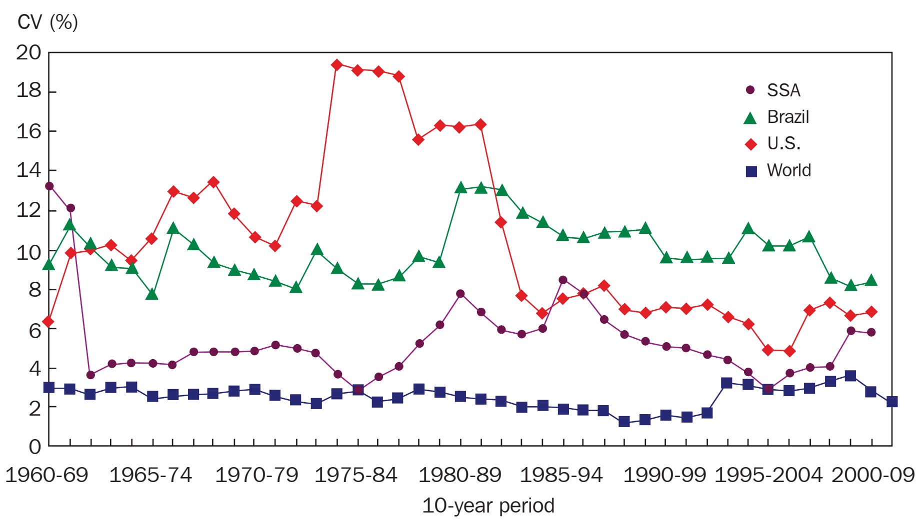

Fig. 5. Ten-year moving coefficient of variation (CV) of production in sub-Saharan Africa (SSA), Brazil, the United States, and the world.

Within Asia, the variability of production has been substantially higher in South Asia than in Southeast Asia (Fig. 6, which shows production variability in the three main subregions of Asia, plus eastern India). The dominance of rainfed rice in South Asia (especially in eastern India, which accounts for a substantial share of rice area) can partly explain this spatial pattern. The severe droughts in the late 1990s and early 2000s resulted in substantial reductions in rice production in India—especially in largely rainfed eastern India. In contrast, Southeast Asian rice production has become more stable over time and continues to remain so despite some production losses during droughts and floods.

In the case of East Asia, production variability in earlier years was similar to that of Southeast Asia but has increased somewhat in recent years after an initial decline. In recent years, the variability of rice area has increased in China (which dominates the trend in East Asia) as farmers have reduced their rice area by growing a single crop of rice instead of two crops of rice per year as was common previously. This has raised production variability although yield instability has largely remained constant after a substantial decline in the 1980s. The adjustment in area occurs mainly in response to farm labor shortages arising from China's rapid economic growth.

Rice production variability in other major rice-growing parts of the world (U.S., Brazil) is higher relative to Asia. This is mainly because the rice-growing areas in these countries are smaller, and thus more likely to experience a shock that affects a large part of the area. The same applies to sub-Saharan Africa, where the current rice area is relatively small, although it has been increasing over time.

Overall, the technological and other changes that led to rapid production growth during the Green Revolution also resulted in more stable production of rice worldwide.

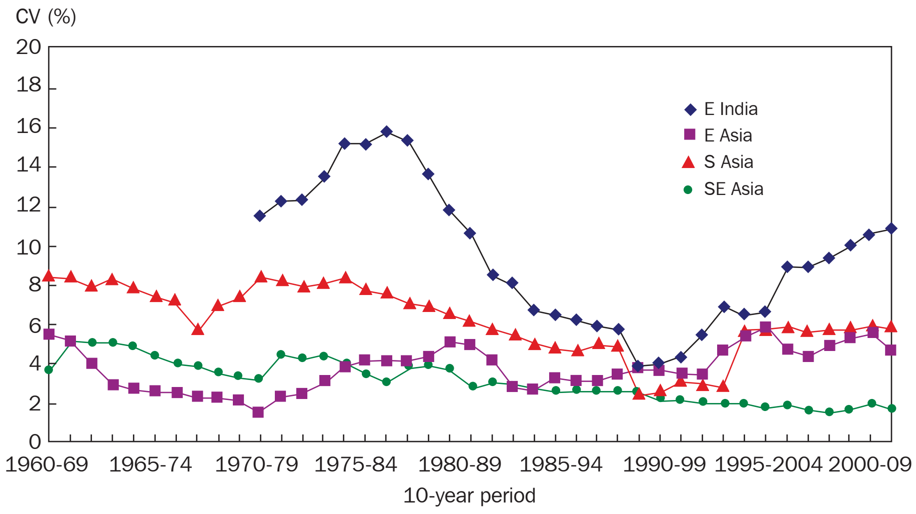

Fig. 6. Ten-year moving coefficient of variation (CV) of production in eastern India (E India), East Asia (E Asia), South Asia (S Asia), and Southeast Asia (SE Asia).

Thus, both growth and stability in rice production were largely achieved simultaneously at the global level. It is unclear whether the tendency toward an increase in the 10-year moving CV of production in recent years, especially in some rainfed areas, is the effect of major production shortfalls due to temporary aberrations or something of a longer-term nature. It is important to note that the moving CV of yield has, however, generally decreased over time at the global level and is lower now than at the start of the Green Revolution.

Summary and key messages

Rice is by far the world's most important food crop for the poor—it supplies 27% of the calories in low- and lower-middle-income countries, more than any other crop. A large majority of it is grown in Asia, but rice area harvested has expanded in Africa in recent decades and is also of growing importance in African diets. Worldwide, an estimated 144 million farm households grow rice, most certainly more than for any other crop.

Irrigation is more important for rice than for any other major crop—62% of rice area is irrigated, whereas the corresponding percentages for wheat and maize are half that or less. Further, expansion of public surface irrigation systems and private groundwater systems has led to an increasing share of irrigation in rice area over time.

Yield growth has historically accounted for most of the tremendous growth in rice production, but yield growth has slowed in recent years to rates below the rate of population growth. Furthermore, growth in area harvested is much slower today than it was in the past, as the lands most suitable for rice are already under cultivation. Thus, it will be a major challenge to increase yield growth in the future so as to enable the world to feed a growing population at prices that are affordable to the poor. This goal has not yet been accomplished, as evidenced by the large numbers of people around the world who are still undernourished (FAO 2010c).

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Notes

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Appendix. Calculation of number of rice farms in the world

We used data from the 33 countries with the largest rice area harvested. These countries collectively accounted for 97.3% of rice area harvested in the world in 2008 (area harvested data from FAO 2010a). For 16 of these 33 countries, there were data on the number of rice holdings reported in the agricultural censuses from the World Census of Agriculture 2000 Round (FAO 2010b). These 16 countries are India, Indonesia, Philippines, Pakistan, Brazil, Japan, Nepal, U.S., Lao PDR, Egypt, Tanzania, Malaysia, Iran, Mali, Ecuador, and Italy (listed in descending order of rice area harvested).

There were no data on rice holdings for the other 17 countries, so we used different methods. For six of these countries (China, Bangladesh, Thailand, Myanmar, Vietnam, and Sri Lanka), we calculated the physical area devoted to rice from Huke and Huke (1997) by subtracting irrigated dry-season area from total rice area harvested (this assumes that all farmers who grow a dry-season irrigated rice crop are double-cropping rice, while no other farmers double-crop). We then divided this physical area by average farm size as reported in the World Census of Agriculture 2000 Round. While the Huke and Huke (1997) data refer to the mid-1990s, and the census data generally refer to the period 2000-05, it is reasonable to combine these two sources because an examination of annual data from IRRI (2010) with the data in Huke and Huke (1997) showed that rice area did not change substantially from the mid-1990s to 2005 in the countries covered by Huke and Huke (1997).

For another six countries without data in Huke and Huke (1997), we used rice area harvested from FAO (2010a), assumed a rice cropping intensity of one, and divided by average farm size as reported in the World Census of Agriculture 2000 Round. In descending order of rice area harvested, these countries are Madagascar, Guinea, Colombia, Democratic Republic of the Congo, Côte d'Ivoire, and Peru. We used census data from the 1990 round for the Democratic Republic of the Congo and Peru, as there are no Round 2000 data for these countries.

The remaining five countries are Cambodia, Nigeria, Sierra Leone, Republic of Korea, and the Democratic People's Republic of Korea (DPRK). None of these countries had census data with the exception of the Republic of Korea (ROK), but its census did not report average farm size. For Cambodia, we used the physical rice area from Huke and Huke (1997) as described above, and divided by the average farm size in Thailand. For Nigeria and Sierra Leone, we used rice area harvested from FAO (2010a), assumed a rice cropping intensity of one, and divided by the average farm size in Côte d'Ivoire. For the ROK, we used the total number of farm holdings as reported in the census, and multiplied by the share of rice area harvested in total crop area harvested. Finally, for the DPRK, we assumed the same farm size as in the ROK. With this assumption, we obtained the number of rice farms in DPRK by taking the ratio of rice area harvested in DPRK to rice area harvested in ROK, and then multiplying this ratio by the number of rice farms in ROK.

Finally, to account for the remaining countries in the world that account for 2.7% of rice area harvested, we scaled up our total number as calculated above by a factor of 1/0.973 = 1.028. This led to a final result of 144 million rice farm households (please notify the authors if you would like to share improved country-specific data sources to improve the accuracy of this number).

Rice and structural transformation

C. Peter Timmer

Introduction

No country has been able to sustain a rapid transition out of poverty without raising productivity in its agricultural sector (if it had one to start—Singapore and Hong Kong are exceptions). The process involves *a successful structural transformation* in which agriculture, through higher productivity, provides food, labor, and even savings to the process of urbanization and industrialization. A dynamic agriculture raises labor productivity in the rural economy, pulls up wages, and gradually eliminates the worst dimensions of absolute poverty. Somewhat paradoxically, the process also leads to a decline in the relative importance of agriculture to the overall economy, as the industrial and service sectors grow even more rapidly, partly through stimulus from a modernizing agriculture and migration of rural workers to urban jobs, and partly because of a relative decline in demand for products from the agricultural sector. The purpose of this chapter is to translate the historical lessons from structural transformation into an understanding of the connections between the sectoral composition of economic growth and reductions in poverty, and then to understand the special role of rice in the process. It draws on a long body of work over the past four decades (Timmer 2010).

Structural transformation in a historical perspective

Structural transformation is the defining characteristic of the development process, both cause and effect of economic growth (Syrquin 2006). Four quite relentless and interrelated processes define structural transformation: a declining share of agriculture in gross domestic product (GDP) and employment (Fig. 1); rural-to-urban migration that stimulates the process of urbanization; the rise of a modern industrial and service economy; and a demographic transition from high rates of births and deaths (common in backward rural areas) to low rates of births and deaths (associated with better health standards in urban areas).

The final outcome of structural transformation, already visible on the horizon in rich countries, is an economy and society in which agriculture as an economic activity has no distinguishing characteristics from other sectors, at least in terms of the productivity of labor and capital. This stage also shows up in Figure 1, as the gap in labor productivity between agricultural and nonagricultural workers approaches zero when incomes are high enough and the two sectors have been integrated by well-functioning labor and capital markets.

All societies want to raise the productivity of their economies. That is the only way to achieve and sustain higher standards of living. The mechanisms for doing this are well known in principle if difficult to implement in practice. They include the use of improved technologies, investment in higher educational and skill levels for the

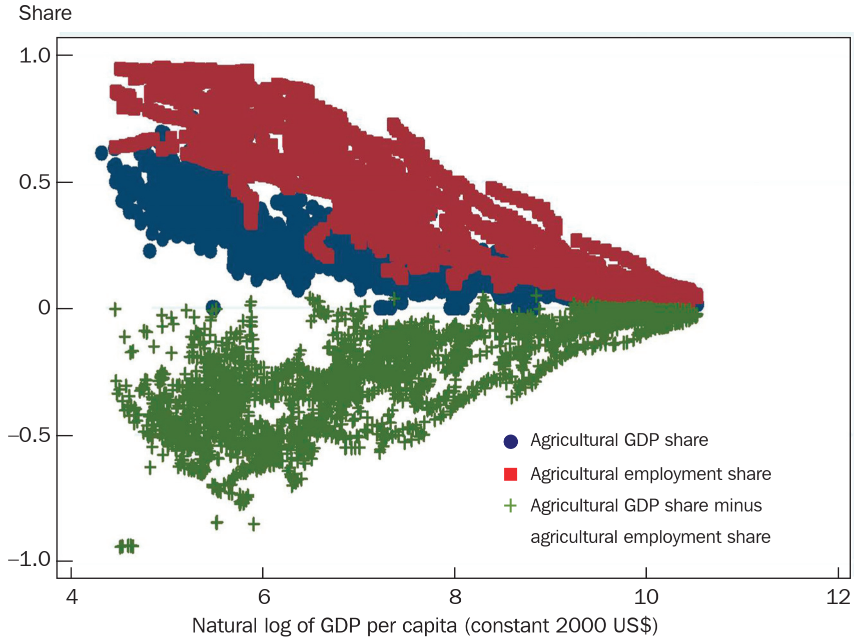


Fig. 1. Structural transformation in 86 countries from 1965 to 2000. Source: Timmer and Akkus (2008).

labor force, lower transaction costs to connect and integrate economic activities, and more efficient allocation of resources. The process of actually implementing these mechanisms over time is the process of economic development. When successful, and sustained for decades, it leads to a structural transformation of the economy.

Structural transformation complicates the division of the economy into sectors—rural versus urban, agricultural versus industry and services—for the purpose of understanding how to raise productivity levels. In the long run, the way to raise rural productivity is to raise urban productivity, or, as Chairman Mao crudely but rightly put it, "the only way out for agriculture is industry." Unless the nonagricultural economy is growing, there is little long-run hope for agriculture. At the same time, the historical record is very clear on the important role that agriculture itself plays in stimulating the nonagricultural economy (Timmer 2002).

This chapter explains the historical patterns of structural transformation and determines empirically (1) whether the patterns have been changing over the past four decades, (2) whether Asian patterns are different, and (3) whether the special nature of rice economies helps explain the difference.

In the early stages of structural transformation in all countries, there is a substantial gap between the share of the labor force employed in agriculture and the share of GDP generated by that work force. Figure 1 shows that this gap narrows with higher incomes. This convergence is also part of structural transformation, reflecting better integrated labor and financial markets. The role of better technology on farms as a way to raise incomes in agriculture is controversial. Most of the evidence suggests that gains in farm productivity have been quickly lost (to farmers) in lower prices and that income convergence between agriculture and nonagriculture is driven primarily by the labor market (Gardner 2002, Johnson 1997). The lower prices for farm output are the joint result of rising supply and limited growth in demand because of Engel's Law—the income elasticity of demand for food is less than one.

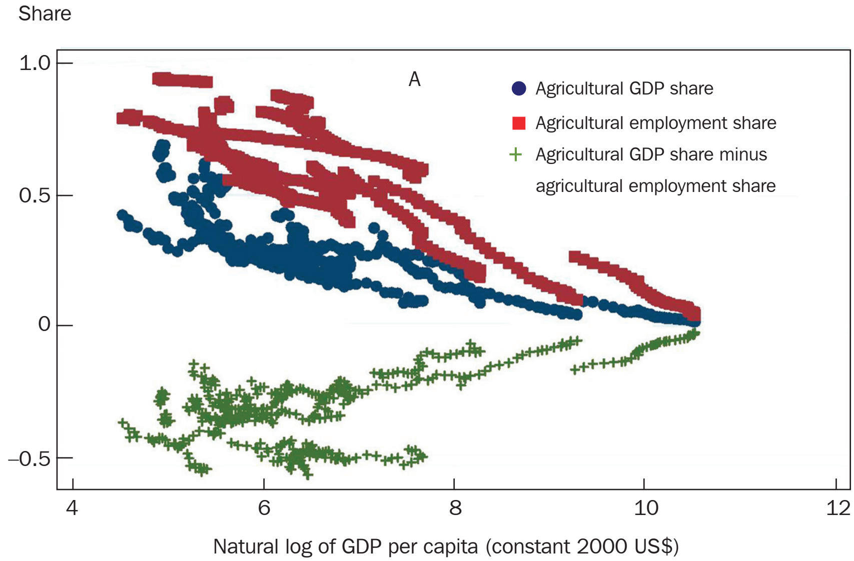
In many countries, this structural gap actually widens during periods of rapid growth, a tendency seen in even the earliest developers, the now-rich OECD countries. When overall GDP is growing rapidly, the share of agriculture in GDP falls much faster than the share of agricultural labor in the overall labor force. The turning point in the gap generated by these differential processes, after which labor productivity in the two sectors begins to converge, has also been moving to the right over time, requiring progressively higher per capita incomes before the convergence process begins.

This lag inevitably presents political problems as farm incomes visibly fall behind incomes being earned in the rest of the economy. The long-run answer, of course, is faster integration of farm labor into the nonfarm economy (including the rural, nonfarm economy), but the historical record shows that such integration takes a long time. It was not fully achieved in the United States until the 1980s (Gardner 2002), and evidence presented here shows that the productivity gap is increasingly difficult to bridge through economic growth alone. *This lag in real earnings from agriculture is the fundamental cause of the deep political tensions generated by structural transformation, and it is getting worse.* Historically, the completely uniform response to these political tensions has been to protect the agricultural sector from international competition and ultimately to provide direct income subsidies to farmers (Lindert 1991). One purpose of this chapter is to understand how the political economy of this process is driven by structural transformation itself.

Structural transformation in Asia is different

At first glance, the 13 Asian countries included in the sample seem to have a similar pattern of structural transformation between 1965 and 2000 as the 73 non-Asian countries (Fig. 2). Since the Asian sample includes some of the fastest-growing countries during that time period (Japan, Republic of Korea, Malaysia, Thailand, and Indonesia), the visual evidence is reassuring that there is in fact a common, long-run pattern of structural transformation.

Statistical analysis, however, confirms that there are important differences in the patterns. In particular, Asian countries have a very different pattern from non-Asian countries of agricultural employment changes with respect to per capita incomes. In addition, the impact of agricultural terms of trade on the share of labor employed in agriculture is *positive* and significant for the Asian sample, whereas it is *negative* and significant for the non-Asian sample. In this, the Asian pattern contrasts with the overall sample as well (Timmer 2009).



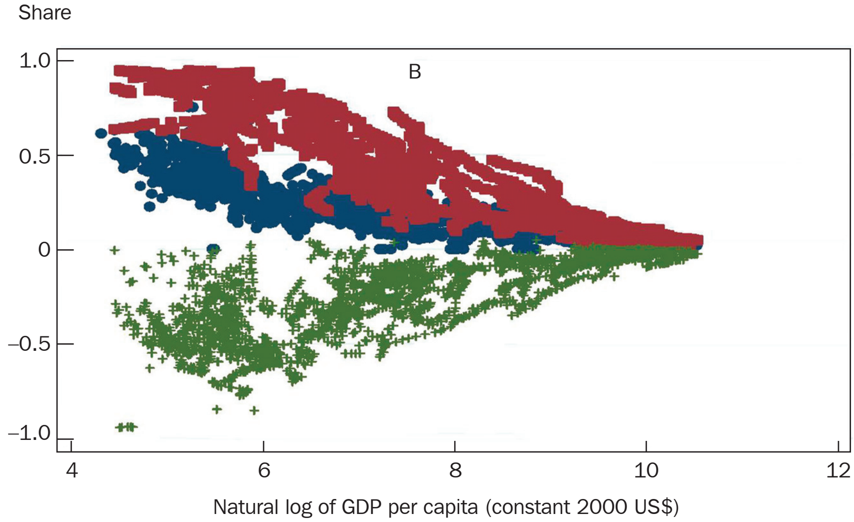


Fig. 2. Structural transformation for (A) 13 Asian countries and (B) 73 non-Asian countries. Source: Timmer and Akkus (2008). (The 13 Asian countries are Bangladesh, China, India, Indonesia, Japan, Republic of Korea, Malaysia, Nepal, Pakistan, Papua New Guinea, the Philippines, Sri Lanka, and Thailand.)

The impact is fairly clear—Asian countries were able to use agricultural terms of trade as a policy instrument for keeping labor employed in agriculture, a pattern not seen in the rest of the countries in the sample, perhaps because of the importance of rice in Asian agriculture, and hence in determining terms of trade. Average economic growth in the Asian sample was faster than in the rest of the countries, and the rapid decline in the share of GDP from agriculture reflects this.

The implication is that Asian countries provided more price incentives to their agricultural sectors over this time period as a way to prevent the movement of labor out of agriculture from being "too fast." Certainly the pattern of movements in agricultural terms of trade for the two sets of countries is strikingly different, with Asian countries seeing a long-run decline at half the pace of the non-Asian countries (Fig. 3). The political economy of these choices is explored in the following section, in which agricultural terms of trade are split into two components, one dependent on world prices for agricultural commodities and energy, the second being the residual that better reflects domestic factors in the formation of agricultural terms of trade.

The reasons for these differences have been the source of considerable debate. An explanation that resonates with the empirical record is that Asian countries were more concerned about providing "macro" food security in urban markets and "micro" food security to rural households because of large and dense populations farming on very limited agricultural resources. Political stability, and with it the foundation for modern economic growth, grew out of the provision of food security that connected poor households to improved opportunities. Stabilizing agricultural terms of trade, made possible because of the large weight of rice in the economy, was an important component of this strategy.

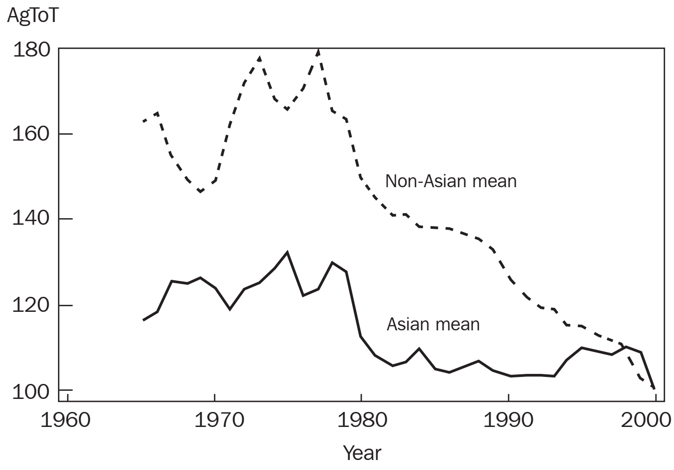


Fig. 3. Asian/non-Asian average agricultural terms of trade (AgToT) change. Source: Timmer and Akkus (2008).

The political economy of agricultural policy: the Asian difference

The uniqueness of some country paths of structural transformation and the distinct patterns seen earlier for Asia suggest that country-specific policies have the potential to alter not just the rate of economic growth, a result that is well known, but also the structural character of that growth. That potential has sparked a flurry of interest in the determinants of "pro-poor growth," defined to mean rapid economic growth that reaches the poor in at least proportionate terms (Besley and Cord 2007).

This chapter is no place to review this entire debate, but it is possible to examine the impact on structural transformation of policy choices in one especially important area—agricultural prices. The key role of agricultural terms of trade (AgToT) in conditioning the path of structural change has already been raised. But these are the *actual* terms of trade reflected in an economy, not necessarily those desired by policymakers. It is possible to go a step further to examine those policy desires, what drives them, and their impact.

Most agricultural price policies are implemented through either trade interventions or subsidies. The goal here is *not* to understand the realities of actual agricultural trade policies—as designed and implemented. For that, the update of the classic Krueger et al (1991) study of agricultural price distortions being led by Kym Anderson is providing much valuable information (Masters 2007, Anderson 2009). Instead, the goal of this section is to examine how agricultural price policy evolves over the long-run process of structural transformation.

In this analysis, AgToT are used as a starting point to find a quantifiable proxy for *desired* agricultural trade policy. The AgToT can be calculated easily as the ratio between the GDP deflator for agricultural value added in national income accounts and the GDP deflator for value added in the rest of the economy. As a result, the analysis focuses exclusively on the *price effects* of agricultural trade policy and does not analyze quantity effects separately.[1] Thus, the emphasis is on understanding desired domestic agricultural price policy and its quantifiable impact, with the mechanics of implementation largely ignored.

Of course, agricultural price *policies* are only one of the many variables that influence the actual domestic AgToT. However, many of the influencing variables are beyond the direct influence of policymakers, such as the real exchange rate, international commodity prices, and the changing structure of the economy during economic development (Timmer 1984a, b). Agricultural trade policies are, by design, things policymakers can change according to their priorities. When we control for the exogenous factors over the process of development, the changing level and impact of agricultural price policies can be identified. That is the approach taken here.

Somewhat ironically, the response of Asian countries to the growing gap in labor productivity between the agricultural and nonagricultural sectors is less sensitive than in non-Asian countries. The irony, of course, is that Asian countries have used

[1]Quantity effects that impact food consumption are often more important for food security and nutritional well-being than price effects that are measured in markets. Such effects are not the main focus of the analysis here. See Timmer (2005a) for treatment of the food security dimensions.

agricultural price policy very aggressively to protect their farmers, especially in the rapidly growing countries of East Asia (Anderson 1986). Their agricultural terms of trade declined at only half the rate as for non-Asian countries, despite being subject to the same global market forces (Fig. 3). But the very speed of the Asian transformation, and the greater concentration on raising productivity of small farmers, means that the actual coefficient of policy response to the gap between the share of agriculture in GDP and its share in the labor force (the sectoral Gini) is smaller.

Asian countries devoted greater policy attention to agriculture across the board, and had the advantage of more equal landholdings than in most other countries. As a result, Asian countries were able to generate a far more rapid and equitable pattern of economic growth (there are several exceptions, the Philippines being perhaps the most obvious). The sheer pace of growth created great political pressures to assist agriculture during the transformation process, but in comparative terms non-Asian countries had to resort to price policy interventions more heavily in response to rapidly worsening income distribution from less rapidly growing economies. That is, the economies of Asian countries responded more flexibly to movements in their agricultural terms of trade, which somewhat paradoxically meant that Asian policymakers could respond somewhat less aggressively to a growing gap in sectoral incomes. They had kept the gap from growing too fast in the first place.

The broader role of agriculture revealed in these patterns extends well beyond agricultural price policy, and it clearly is powerful enough to influence the basic patterns of structural transformation. The Asian patterns are sharply different from patterns in the rest of the developing world. Why? Are the special features of rice cultivation and consumption responsible for Asia's distinctiveness?

The changing role of rice in Asia

It is hard to imagine a more compelling picture of the changing role of rice in the global and Asian economies than the simple black-and-white data presented in Table 1. The objective of the table is simple, to show how structural transformation has altered the role of rice in the agricultural and overall economies of Asia and the rest of the world. The calculations, however, turn out to be complex. It is no wonder that these results will strike most readers as "new" and, perhaps, surprising.

Still, the approach is straightforward. The first step is to determine the share of cereal production in total agricultural production, something that is now possible with the new FAO production index that reports these values in 1991 international dollars, by country and for regional aggregates (Table 1, sections 1–3). At a global level, the share of cereals did not change much from 1961 to 2007, rising slightly from 1961 (21.4%) to 1980 (24.4%), reflecting the productivity impact of the new technologies for rice and wheat. By 2007, however, the share of cereals had declined to 21.3% of total agricultural production, virtually unchanged from the 1961 value.

There is substantial regional variation in this pattern. The share of cereals in East Asia's total agricultural production rose from 33.7% in 1961 to 37.9% in 1980, before falling sharply to 19.4% in 2007. A rapid agricultural transformation was going on in East Asia after 1980, both cause and effect of the rapid economic growth in the region and its accompanying structural transformation. South Asia saw similar but more modest changes, as did Southeast Asia, from a higher base. Africa, of course, relies much less heavily on cereals in its agricultural production, and there was little change in that pattern from 1961 to 2007.

The next step is to determine the role of rice in cereal production, something not possible directly from the FAO production index. An alternative approach is straightforward, however. Sections 4–7 in Table 1 use physical production of total cereals and of rice to calculate the share of rice in the total. In these calculations, the amount of rough rice is used in the comparison, despite the milling losses needed to produce an edible product. Although this approach tends to overstate the role of rice, an offsetting factor is that rice tends to be more valuable as a foodstuff per unit of weight, so the end result is about right. Further, whatever biases are introduced by this approach will not change much over time, and it is primarily the temporal patterns that are of interest.

Again, at a global level, the share of rice in total cereal production did not change a lot between 1961 and 2007, starting at 24.6% and rising gradually to 28.1%. But the regional patterns of change are quite dramatic. First, it is obvious that Asia relies far more heavily on rice than the rest of the world even as East Asia's share of rice fell steadily from 56.2% in 1961 to 43.0% in 2007. A similar but slower decline from a higher base is seen in South Asia. Southeast Asia is very heavily dependent on rice—it accounted for 90.6% of cereal production in 1961 and still accounted for 85.9% of cereal production in 2007.

Perhaps surprisingly, Africa has steadily increased its production of rice over the past half century (by 3.5% per year since 1961), and the role of rice in overall cereal production. In 1961, rice was 9.3% of total cereal production in Africa, and this share rose steadily to become 15.2% in 2007. Rice has become a significant cereal crop in Africa.

The final three sections of Table 1 show the calculations needed to understand the changing role of rice in overall agricultural production and for the entire economy. In section 7, rice as a share of total agriculture is calculated by multiplying the values in section 3 by the values in section 6. The results are just arithmetic, but are interesting nonetheless. Rice has been about 5–6% of agricultural production since 1961, but the share varies enormously by region. In East Asia, rice's share has dropped from about a fifth of agricultural output to less than a tenth. Rice remains more significant in South Asia, contributing 15.2% in 2007. In Southeast Asia, rice contributed 40.2% of agricultural output in 1961, a figure that has dropped steadily, but slowly, since then. In 2007, rice still contributed 32.0% of agricultural output in Southeast Asia.

The share of rice in Africa's agriculture is small, just 1.48% in 1961. But, unlike the patterns in Asia, the share of rice in Africa is rising; it was 2.34% in 2007. Although still a small factor in Africa's overall agricultural production, it is clearly a commodity with a promising future.

Section 8 of the table reports the share of agricultural value added in overall GDP, a value reported regularly in all countries' national income accounts and available from

Table 1. Rice and structural transformation: 1961-2007.

Item	Average values					
	1961	1980	2007	1961-80	1980-2007	1961-2007
1. Total agricultural production value (1991 US$)						
World	607.5	956.0	1,692.5	2.42	2.14	2.25
East Asia	73.8	142.3	414.1	3.52	4.04	3.82
South Asia	68.2	104.6	250.9	2.28	3.29	2.87
Southeast Asia	23.4	45.3	115.5	3.54	3.53	3.53
Africa	40.2	61.6	130.4	2.25	2.82	2.59
2. Total cereal production value (1991 US$)						
World	130.2	233.6	360.1	3.12	1.62	2.24
East Asia	24.9	54.0	80.3	4.16	1.48	2.58
South Asia	22.4	36.5	68.9	2.60	2.38	2.47
Southeast Asia	10.4	19.3	43.1	3.31	3.02	3.14
Africa	6.4	10.0	20.1	2.39	2.62	2.52
3. Cereal production as % of total agricultural production[a]						
World	21.4	24.4	21.3			
East Asia	33.7	37.9	19.4			
South Asia	32.8	34.9	27.5			
Southeast Asia	44.4	42.6	37.3			
Africa	15.9	16.2	15.4			
4. Cereal production (million tons)						
World	877.0	1,550.2	2,351.4	3.04	1.56	2.17
East Asia	140.3	306.2	480.3	4.19	1.68	2.71
South Asia	120.8	198.0	375.0	2.63	2.39	2.49
Southeast Asia	50.8	95.8	216.1	3.40	3.06	3.20
Africa	46.3	72.6	139.8	2.40	2.46	2.43
5. Rough rice production (million tons)						
World	215.6	396.9	659.6	3.26	1.90	2.46
East Asia	78.9	163.0	206.7	3.89	0.88	2.12
South Asia	73.6	112.2	206.9	2.24	2.29	2.27
Southeast Asia	46.0	84.5	185.7	3.25	2.96	3.08
Africa	4.3	8.6	21.3	3.71	3.41	3.53
6. Rough rice as % of cereal production[b]						
World	24.6	25.6	28.1			
East Asia	56.2	53.2	43.0			
South Asia	60.9	56.7	55.2			
Southeast Asia	90.6	88.2	85.9			
Africa	9.3	11.9	15.2			
7. Rice as % of agriculture[c]						
World	5.3	6.3	6.0			
East Asia	18.9	20.2	8.3			
South Asia	20.0	19.8	15.2			

Table continued.

Table continued.

Southeast Asia	40.2	37.6	32.0
Africa	1.5	1.9	2.3
8. Agricultural value added as % of GDP (from World Bank)			
World	10	7	3
East Asia[d]	36	29	12
South Asia	42	35	18
Southeast Asia[d]	36	29	12
Africa	22	19	15
9. Rice as % of GDP[e]			
World	0.55	0.41	0.17
East Asia	6.80	5.86	1.00
South Asia	8.40	6.93	2.74
Southeast Asia	14.47	10.90	3.84
Africa	0.33	0.37	0.35

[a]Values in Item 3 are obtained by dividing values in Item 2 by values in Item 1. [b]Values in Item 6 are obtained by dividing values in Item 5 by values in Item 4. [c]Values in Item 7 are obtained by multiplying values in Item 3 by values in Item 6. [d]East Asia and Southeast Asia are combined in the World Bank regional aggregates for agricultural value added as a % of GDP. [e]Values in Item 9 are obtained by multiplying values in Item 7 by values in Item 8.

the World Development Indicators (WDI) published by the World Bank. In its crudest form, this is structural transformation. For the entire world, agriculture contributed a bit over 10% of economic output in 1961 and a bit less than 3% in 2007. These low numbers are the result of the economic dominance of rich countries in global GDP, and the very small contribution of agriculture in these economies.

Asia is much more dependent on agriculture. The World Bank reports these data for East and Southeast Asia combined, and the share of agricultural value added in overall GDP declined from 36% in 1961 to 12% in 2007.[2] The share of agriculture in South Asia's economy is higher, starting at 42% in 1961 and declining to 18% in 2007. The share of agriculture in Africa's economy is surprisingly low, but it has declined little, from 22% in 1961 to 15% in 2007.

The contrast between Asia and the rest of the world is sharp: in 1961, agriculture was 3.7 times as important to Asian economies as to the world as a whole (taking the simple average of East Asia and South Asia). This ratio had climbed to 5.2 times as important in 2007. Despite the rapid transformation of Asian economies, agriculture remains very important (which is mostly because Asian economies remain, on average, very poor).

Finally, section 9 provides the "bottom line" to our question: how has the role of rice changed? At a world level, rice accounted for just over one half of one percent of GDP in 1961. Over the next half century, the share of rice in GDP for the entire

[2]If the major agricultural producers of Southeast Asia (Indonesia, Thailand, Philippines, Vietnam, and Malaysia) are examined as a regional aggregate separately, the share of agricultural value added to GDP was 40.9% in 1961, 38.6% in 1970, 26.9% in 1980, 21.9% in 1990, 16.4% in 2000, and 14.5% in 2007. Most of the remainder of the World Bank regional aggregate of "East Asia and the Pacific" is then composed of China. The share of agriculture in China's GDP was 36%, 35%, 30%, 27%, 15%, and 11%, from 1961 to 2007, by decades.

world fell to just 0.174% of GDP. In terms of overall economic output on a global scale, rice is a very small factor.[3]

In Asia, rice is far more important, although its share in national economies is not as large as many observers think. Even in 1961, rice accounted for just 6.8% of GDP in East Asia, 8.4% in South Asia, and 14.5% in Southeast Asia. Naturally, because of structural transformation and the declining role of agriculture in successfully growing economies, and agricultural transformation, in which farmers diversify out of low-valued rice production, the share of rice in Asian economies (share of GDP) has declined very rapidly. In 2007, it was just 1.0% in East Asia, 2.7% in South Asia, and 3.8% in Southeast Asia. So, even in Asia, rice is less important *economically* than livestock, construction, or transportation, even banking. Total employment in the rice economy may still rival these other sectors, but that is because the economic returns to working in the rice sector are so low—a failure of structural transformation to absorb rural workers fast enough.

Why rice-based food systems are different[4]

The formation of rice prices in world markets has long interested scholars and policymakers.[5] Nearly half the world's population consumes rice as a staple food and it is typically produced by small farmers in Asia using highly labor-intensive techniques. (Ninety percent of the world's rice harvest is produced in Asia.) Rice is mostly consumed within a short distance of where it is produced, with international trade less than 30 million tons out of a global production of nearly 440 million tons (milled rice equivalent)—only 7–8% of rice produced crosses an international border.[6] Still, the world market for rice provides essential supplies to importing countries around the world, and the prices set in this market provide signals to both exporting and importing countries about the opportunity cost of increasing production and/or consumption. It is disconcerting to exporters and importers alike if these market signals are highly volatile.

Part of the longstanding interest in the world rice market has been precisely because it has been so volatile. The coefficient of variation of world rice prices has often been double that of wheat or maize for decades at a time. Understanding this volatility has been difficult because much of it traces to the residual nature of the world rice market, as both importing and exporting countries stabilize rice prices internally by using the world rice market to dispose of surpluses or to meet deficits via imports. Thus, supply and demand in the world market are a direct result of political decisions in a number of Asian countries. Rice is a very political commodity (Timmer and Falcon 1975).

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[3]It should be emphasized that these are production shares of rice to value added and do not include the value of processing and marketing. The share of rice at the level of consumption is probably about half again as large.

[4]This section is based on Timmer (2010)

[5]The early standard works are Wickizer and Bennett (1941) and Barker and Herdt (with Beth Rose) (1985).

[6]Information on the world rice market is available at http://usda.mannlib.cornell.edu/usda/ers/89001.

But volatility in rice prices is also driven by the structure of rice production, marketing, and consumption in most Asian countries, that is, by the industrial organization of the rice economy. Hundreds of millions of small farmers; millions of traders, processors, and retailers; and billions of individual consumers all handle a commodity that can be stored for well over a year in a consumable form if properly milled and warehoused. The price expectations of these market participants are critical to their decisions about how much to grow, to sell, to store, and to consume.

Because virtually no data are available about either these price expectations or their marketing consequences, the world rice market operates with highly incomplete and imperfect information about short-run supply and demand factors. In this, rice is a very different commodity from the other basic food staples, wheat and maize.[7] The difference is important because the multitudes of small-scale agents in the rice economy tend to form their price expectations on the basis of the same limited information, thus destablizing stockholding and prices.

When the political dimensions and the different market structure for rice are integrated into actual price formation, the scope for extreme volatility is clear. Understanding the proximate causes of unstable rice prices requires understanding both factors, and how they contribute to the formation of price expectations on the part of market participants. These expectations can drive "destabilizing speculative behavior" among millions, even billions, of market participants, such that price formation seems to have a large, destabilizing, speculative component.[8] If so, and price behavior late in 2007 and early 2008 suggests this might be a serious problem, what stabilizing activities might be undertaken to make the world rice market a more reliable venue for imports and exports, with price signals that reflect long-run production costs and consumer demand rather than short-run panicked behavior?

To answer this question, simple supply and demand models are a start. The difference between short-run responses to price changes, and those responses after full

[7]This difference was pointed out clearly in Jasny's classic study of *Competition Among Grains* (Jasny 1940). He justifies his exclusion of rice from the study with the following observation: "The Orient is a world by itself, with its own climate, diet, and economic and social setup, and this makes it easy for us to omit it. The inclusion of rice would mean the discussion of two worlds. The writer would be satisfied to have mastered one." (p. 7) The sharp difference between rice-based economies and those based on wheat or corn is also stressed by Bray (1986) and Oshima (1987).

[8]The emphasis here on *destabilizing* expectations and subsequent speculative price behavior is meant to contrast with the normally *stabilizing* role that routine speculative activities play. Unless speculators buy during the harvest, store grain, and sell during the off-season, seasonal price movements would be much larger than they are without these normal speculative activities. Of course, seasonal prices must rise from their harvest lows to their peak just before the new harvest, or these stabilizing speculative investments would not be made. It is difficult to define precisely the difference between stabilizing and destabilizing speculation. Even agents who engage entirely in the financial derivatives of commodities, such as futures, options, and swaps, can contribute to the liquidity of the underlying markets and thus help support the stabilizing function of speculation. But when herd behavior sets in and most financial speculation is in only one direction, the potential to generate bubbles and less stable prices is clear. Much more analytical and empirical work needs to be done on the role of financial instruments as they influence commodity prices in spot markets (Robles et al 2009).

adaptation is possible in the long run, is crucial and a conceptual model highlights the importance of these differences for understanding current prices. History matters.

But storage and price expectations also become important for storable commodities in the short run—the length of time the commodity can be stored—about a year for rice. A model of the "supply of storage," a staple of commodity market analysis for more than half a century, can be used to understand the factors affecting price expectations, and price formation, in the short run. This model is very powerful in its ability to explain hoarding behavior and subsequent impact on prices.

The supply of storage model is less successful in explaining the impact on spot market prices of futures market prices that are driven by "outside" speculators, that is, those who have no interest in owning the actual commodity but are investing solely on the basis of expected price changes on futures markets. The role of outside speculators in commodity price formation is an old debate, although one that has usually not included rice because of the thinness of rice futures markets. The potential of outside speculators to induce destabilizing price formation is a major element of this debate.

The importance of understanding the role of speculation in causing spikes in rice prices was seen clearly in the sharp run-up in world prices between October 2007 and May 2008. Hoarding by farmers, traders, consumers, and even countries was a major cause of the price spike, especially in Vietnam and the Philippines (Timmer 2010).

Long-run price relationships among the staple cereals

Most commodity market analysts think there is a long-run relationship among the prices of staple grains, based on commodity substitutions in both production and consumption (Timmer et al 1983). Mitchell (2008), for example, argues that wheat prices historically have averaged about 60–80% of the price of rice (and thus were far "too high" in early 2007, reflecting speculative pressures in the wheat market). Table 2 presents results from analyzing the long-run relationship between prices of the three basic cereal staples, rice, wheat, and corn (maize), since 1900.

There has clearly been a long-run decline in the prices of all three cereals. This decline has a basic commonality, as all three commodities have trend price declines of more than 1.0% per year. Further, this decline accelerated after the mid-1980s, again for apparently common reasons (Fig. 4).

Two basic models of long-run price formation are tested in Table 2 for each of the three basic food cereals, rice, wheat, and maize. The first asks simply what the long-run time trend in real prices is, without further explanatory variables (Equations 1, 3, and 5). There can be no mistaking the sharp downward trend, either econometrically in Table 2 or visually. The trend decline for rice is 1.34% per year, for maize it is 1.25% per year, and for wheat it is 1.05% per year. The difference between the trend decline for rice and wheat is significant at the 5% level. Something has been driving rice prices down faster than wheat prices over the past century. The difference between the simple trend decline for rice and maize is not significant. The very simplicity of this trend analysis, of course, precludes any attempt at explaining why there are differences in trends.

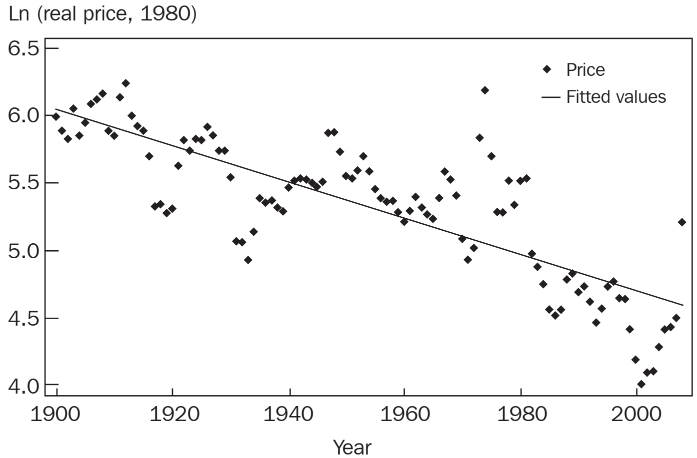

Fig. 4. Long-run trend in real rice prices, 1900-2008. Vertical axis is the natural logarithm of the real price of rice, with the base year 1980. Source: data from Eberstadt (2008), analysis by author.

Table 2. Long-run relationships among rice, wheat, and maize prices, 1900-2008.[a]

	Dependent variable: logarithm of price					
	Rice		Wheat		Maize	
Independent variables	(1)	(2)	(3)	(4)	(5)	(6)
Constant	31.59	11.59	26.02	2.27	29.99	5.80
	(16.7)	(3.9)	(16.5)	(1.1)	(17.2)	(2.6)
Time[b]	–0.0134	–0.0053	–0.0105	–0.0005	–0.0125	–0.0027
	(14.1)	(4.0)	(13.0)	(0.6)	(14.1)	(2.7)
Log rice price	–	–	–	0.19	–	0.13
				(3.2)		(1.9)
Log wheat price	–	0.47	–	–	–	0.77
		(3.2)				(9.3)
Log maize price	–	0.26	–	0.59	–	–
		(1.9)		(9.3)		
Adj. R^2	0.64	0.77	0.61	0.86	0.64	0.87

[a]Robust t-statistics in parentheses. [b]Because the price terms are in logarithms, the coefficient on the time variable can be interpreted as the annual percent "trend" change in the dependent variable. Thus, in Equation 1, the annual rate of *decrease* in rice prices is estimated to be 1.34% per year, before allowance is made for the impact of price changes for other staple food commodities. Holding constant the prices of wheat and maize in each year, the trend decrease in rice prices drops to just 0.53% per year. A similar interpretation holds for the time coefficients for the other commodities.
Source: Data from Eberstadt (2008), analysis by author.

The second model is slightly more sophisticated and starts to tackle the issue of differences in price formation among the three cereals (Equations 2, 4, and 6). This model still tests for the existence of a time trend, but now the trend estimate for the price of each commodity is (statistically) controlled for the prices of the other two commodities in the same year.[9] The results are actually quite dramatic. The downward time trend for wheat disappears altogether, with rice prices (coefficient = 0.19) and maize prices (coefficient = 0.59) both having a highly significant impact on wheat prices.

Maize prices behave in a similar but less dramatic fashion. The time trend is only –0.27% per year, although it is statistically significant. Rice prices have only a marginal impact on maize prices, with a coefficient of 0.13, which is not significant at the 5% level. Wheat prices, however, have a very large impact on long-run maize prices, with a coefficient of 0.77 that is highly significant.

Although somewhat related to wheat and maize prices, rice prices clearly have a different pattern of price formation. The impact of maize prices on rice prices is only marginally significant (as was the case in reverse). Wheat prices have a modest impact, which is statistically significant. Comparing the sum of the two coefficients for each of the three regressions is revealing: the sum for rice (of the maize and wheat coefficients) is 0.73, with an average t-statistic of only 2.6. The total for wheat (of the rice and maize coefficients) is 0.78, with an average t-statistic of 6.3. Maize prices are best explained by the other two commodity prices: the sum of the coefficients is 0.90, with an average t-statistic of 5.6. Clearly, rice prices exhibit substantial independence from maize and wheat prices. This conclusion is also borne out by the adjusted R-squared coefficients for each of the price regressions: rice is "only" 0.77, whereas both maize and wheat are 0.86.

Most significantly, the exogenous time trend for real rice prices, even after controlling for the impact of wheat and maize prices, continues to be substantial and negative, with a significant coefficient of –0.53% per year. Even if maize and wheat prices remained stable in real terms, rice prices would be lower by more than 40% after a century.

There would seem to be two implications of these statistical results. First, both maize and especially rice prices have been driven down by powerful exogenous factors, even after controlling for the general decline in the prices of the other grains. Presumably, differential technological change is the main driver of these negative time trends, although demand growth for rice may have been slower over the long run than for wheat. Because of its role in livestock feeding, however, the demand for maize has grown the fastest of the three cereals, yet it still has a small but significant downward trend in price, after allowing for the general decline in cereal prices. This

[9] Technically, this assumes that the prices are independent of each other in the same year, which is obviously not true if their price formation is determined simultaneously from a common set of exogenous factors. This not a serious problem here, where the issue is simply the impact of the other commodity prices on the "exogenous" time trend. Introducing lagged values would solve the econometric problem without changing the results discussed here.

pattern suggests that differential technological change is probably the main driver of prices over the long run.

Second, rice prices clearly have a life of their own. This is seen in the strong downward time trend when tested alone, in the continued significance of a downward trend when allowance is made for the prices of wheat and maize, and in the relatively small explanatory power of the fully specified price model that allows for these other prices. What causes these long-run differences in price trends?

For the short run, the answer would seem to lie in market structure. It has already been established here that one unique dimension of short-run rice price formation stems from the highly unusual industrial organization of the world's rice economy, with many small producers, traders, retailers, and consumers handling a product that is storable at each stage.

The supply of storage model, in turn, argues that this highly decentralized storage capacity is subject to changes in price expectations on the part of participants all along the supply chain. These expectations become self-fulfilling and lead to episodes of panic buying, and subsequent de-stocking, which sharply destabilize actual prices. Because no one has data on the size of rice stocks in the hands of these multitudinous market participants, their impact on rice price formation is virtually impossible to predict ahead of time. Rice really is "different" in the short run.

Does this difference in market structure also account for the difference in long-run price trends between rice and the other two staple food grains, maize and wheat? Only to a limited extent. The faster downward trend in rice prices, even holding constant the prices of wheat and maize, argues that the long-run equilibrium between supply and demand for rice is shifting down faster than for maize and wheat. Technological change for rice will push the supply curve out. Slower population growth in rice-consuming countries, and a faster transition to very low, even negative Engel coefficients for rice, will account for slower demand growth.[10] Changing consumer tastes could also be a factor.

But the greater variance in the downward trend for rice (the lower R-squared) does suggest that market structure has both long-run and short-run significance. The political economy of high variance in world rice prices is well understood—it leads countries to retreat into autarky, and dump their own instability into a smaller world rice market. One consequence of this drive for self-sufficiency among rice importers is larger overall production than would be expected in a world of free trade. This added production should also contribute to a long-run decline in world prices.

Breaking into this vicious circle, seen clearly in the price spike in late 2007 and early 2008, will require binding agreements, perhaps even contracts, between rice importers and exporters over multiyear periods, not just for short-run trade. Because there seem to be virtually no national or international pressures for such binding agreements, rice is likely to remain a "different" commodity for decades to come.

[10]See the accompanying chapter in this volume by Timmer et al, "Long-run dynamics of rice consumption: 1960-2050," for further discussion of the impact of declining income elasticities of demand for rice.

Rice and the poor

It was noted more than two decades ago that a successful structural transformation has always been painful for rural households (Timmer 1988). Although structural transformation seems to offer the only sustainable pathway out of poverty in the long run, it can be a very challenging process for the poor in the short run. Is there any way to manage the process without hurting the poor? To answer the question, a historical perspective on structural transformation is essential, especially the experiences in the countries of East and Southeast Asia that managed both rapid growth and stability or even improvement in income distribution during the process (World Bank 1993, Ravallion and Chen 2004, Timmer 2004).

Analysis of recent research on "pro-poor" growth suggests that an "Asian" pattern of rural development and poverty reduction exists (Oshima 1987, Besley and Cord 2006, Grimm et al 2007). The common structure involves the evolution of the agricultural sector from a starting point of household subsistence production, through the adoption of new technologies that provide surpluses and rural food security, to more diversified farm activities driven by commercial forces, and finally to the full integration of the agricultural economy into the overall economy.

This structural pattern can be examined from two directions: first, from the perspective of the main *policy concerns* shown by Asian countries at each stage, and the links between these policy concerns and the key economic drivers and mechanisms for change. Asia may have been unique in its early concern for food security, including for rural households, as the main policy focus that mobilized substantial resources on behalf of agriculture (Timmer 2005a). The importance of rice in Asian food security—it accounted for 30% of caloric intake in 2005—and the tenuous (and tense) relationship between domestic rice economies and the world market for rice focused political and economic attention on agricultural productivity in ways not seen in other parts of the world.

For Asia, the Green Revolution technologies for wheat and rice transformed their potential for a domestic approach to food security. When this potential was fully realized, in Indonesia in the early 1980s, in India in the late 1980s, in Bangladesh in the early 1990s, and in Vietnam in the mid-1990s, the policy concern turned to supporting farm incomes in the face of declining world prices for cereals. The "efficient" way to do this was through the next structural phase, into diversification and specialization, and Bangladesh seems to be moving in this direction. The more advanced regions in China are already well down this road. The alternative approach, however, is to maintain farm incomes by protecting the rice sector, using subsidies to keep inputs cheap, and thus to slow the diversification process. Both India and Indonesia are caught in this expensive and distortionary approach. It is impossible to move on to the stage of rapid productivity growth and integration into the overall economy as long as the diversification phase is postponed.

The second perspective on these structural changes is from the point of view of relations between the farm and rural nonfarm sectors. Relatively little attention has been devoted to the rural nonfarm sector in Asia, although the Indonesian experience has been used to stress the importance of Mellor's model of nontradables production, mostly in rural areas, as the key to understanding the role of agriculture in pro-poor growth (Timmer 2006, 2007). But a broader literature helps understand this role more clearly. In particular, there seems to be a structural transformation of enterprises in the rural nonfarm sector that parallels that of agricultural enterprises, as they evolve from very small household-based enterprises into larger firms with "permanent" structures as the place of business. These permanent, rural nonfarm enterprises were the fastest growing part of the Bangladesh economy in the 1990s (World Bank 2004b).

All of the large Asian countries are having a very difficult time transitioning from the "food security" to the "farm income" and on to the "rural productivity" objective for public policy (Timmer 2005b). The difficulties are clearest in India and Indonesia, where the preferred policy mechanism is price protection and input subsidies, not diversification and commercialization. Similar pressures are evident in Bangladesh, Vietnam, and China, but budget pressures and more successful diversification by the market have helped keep the structural retardation under control.

This retardation is seen most clearly in enterprise productivity in the rural nonfarm sector. India and Indonesia are seriously lagging in this regard. China, because of its unique institutional history and experience with town and village enterprises (TVEs), seems to be in the vanguard of rural enterprise development. Bangladesh, because of sheer population density and shrinking agricultural land, is developing productive rural nonfarm enterprises at a surprisingly rapid rate (World Bank 2004b). Bonschab and Klump (2004) suggest that rural nonfarm enterprises should become the leading source of rural employment growth in Vietnam. The problem until now has been the socialist planning legacy and restricted property rights for owners of nonfarm rural enterprises, especially if they appeared to compete with state-owned enterprises. Accordingly, Vietnam has focused more on an urban growth pole model than on diversified rural enterprises. As a consequence, rural to urban migration is a much larger factor in the poverty reduction story in Vietnam than it seems to be in the other countries studied.

Much of India's problem stems from the "structure" of its support to the rural economy, that is, from the relative size of subsidies compared with investments, especially in roads and agricultural research (Fan et al 2004, World Bank 2004a). The political economy of agricultural subsidies in a democracy is well understood, but India is the poorest country to try them on such an extravagant scale. The cost is not just to the budget, although that is high enough. The larger costs seem to be to the agricultural transformation itself, and hence to structural transformation, which is the only long-run hope for India's poor.

A major issue with respect to the role of agriculture in pro-poor growth is the impact of food prices on poverty. In India, Indonesia, and Bangladesh, the story is consistent and unambiguous. Higher productivity in the food-crop sector, especially in domestic rice production, led to lower relative food prices in both rural and urban areas, with very substantial beneficial impact on the poor. In India and Bangladesh, this mechanism may have been the leading contribution of agriculture to pro-poor growth, and any long-run reversal of the pattern would seriously hurt the poor.

The impact of rice prices on the poor in Vietnam is more complex. Much of Vietnam's rapid poverty reduction was driven *directly* by higher incomes in rice-producing households, stimulated to a large extent by the realignment of the exchange rate and consequently greater price incentives for production and export. In some sense, Vietnam's reforms transformed rice from a nontradable to a tradable commodity, with large gains in efficiency and output. But regions less well situated for rapid expansion of rice production, and the poor in urban areas, were probably hurt by this new economic environment. Bonschab and Klump (2004) argue that much of the widening in income inequality across regions was because of differential potential for rice exports.

The Chinese story seems to be radically different. Ravallion and Chen (2004) show that poverty rates fall dramatically when rural producer prices are *higher*, implying that most of the rural poor have their net incomes directly and positively affected by food prices. Because of the nature of the Chinese food marketing system, however, Ravallion and Chen argue that improving terms of trade for farmers is equivalent to removing a tax on their incomes and does not actually have a direct impact on food prices for consumers. If this is the case, then the Chinese example also follows the more general pattern in Asia where lower food prices directly benefit the poor.

The importance of the rural nonfarm economy[11]

Even when comparing five of the largest countries in the world, all of them rice-based food economies in Asia (with apologies to the wheat farmers in Bangladesh, China, and India, and the maize farmers in poorer parts of most of these countries), it is striking how diverse they are, both at one time across countries and within a single country across time. This diversity extends to the role of agriculture in pro-poor growth, in three important ways.

First, the initial conditions and institutional settings for rapid gains in productivity varied enormously in the 1960s, when new rice and wheat technologies became available from the international agricultural research centers (or from domestic centers in China). India had been investing heavily in irrigation, agricultural universities, land reform, and fertilizer production well before the Green Revolution, whereas Indonesia had virtually destroyed what little agricultural infrastructure remained when the Dutch were forced out. Bangladesh took more than a decade to become a functioning country after independence in 1971. Vietnam was prone to famines before 1989 and imported rice to feed even its farm population. Opening its economy and stabilizing macro policy led to a surge in agriculture, but continued socialist controls on private ownership and market restrictions prevented a dynamic rural nonfarm sector from emerging. Migration has become a leading source of poverty reduction in Vietnam. Despite the early success in China with TVEs, rural to urban migration has also been essential there to linking the poor to economic growth.

Second, despite all the temporal and cross-section diversity, a common pattern of structural transformation can be seen. The Asian experience shows clearly that this

[11]The standard reference on the rural nonfarm economy is Haggblade et al (2007).

structural transformation is driven by a successful *agricultural* transformation (Table 1). In turn, the investments in agriculture needed for this transformation, in both policy and financial terms, were driven by a deep political concern for food security (Timmer 2005a). The very integrity of the state was threatened by hunger and famine, whether in democratic India, autocratic Indonesia, or communist Vietnam or China (although the communist countries certainly held out longer in the face of hunger and famine than did the more open societies). This concern for food security drove the transition from subsistence agriculture to rural food surpluses, thus alleviating rural poverty directly, and overall poverty through lower real food prices.

Third, diversity returns again at the next stage. None of these large, rice-based countries has yet managed a successful transition from rural food security to rural productivity through diversification and commercialization. Some countries are more successful than others, as parts of China, Bangladesh, and areas on Java are responding quickly to the economic signals pushing in this direction. But, almost uniformly, policymakers are resisting this transition, apparently because they fear a loss of food security as measured by the relative volume of rice imports.

A reader from outside Asia, seeking lessons for Latin America or Africa from these five countries, would be excused for being totally confused. Gains in food-crop production, stimulated by government investments, subsidies to inputs, and guaranteed output prices, were the initial basis for pro-poor growth in all these countries. *But now those same policy instruments are counterproductive for both growth and the poor*. Agriculture needs to restructure into a diversified and commercialized sector that will have little direct impact on the poor, even through food prices. At this stage, especially in India and Indonesia, agriculture's main impact on poverty is more likely to come through its support for a dynamic rural nonfarm economy, which will be a bridge for the rural poor to cross on their way to jobs in the formal economy.

This role does not show up in econometric tests of agriculture's contribution to poverty reduction, for two reasons. First, this "new" agriculture is still largely nascent, and hence does not appear in the statistical record very clearly. Second, the impact will be through linkages and multipliers that have been hard to conceptualize, model, and estimate, because they depend so crucially on local conditions and institutional context. That does not mean that the role of agriculture in pro-poor growth has diminished to the point of being irrelevant. It does mean that agriculture's role, as always, must be understood in the context of multisectoral and general equilibrium frameworks, not through a sectoral lens alone.

Why rice is still important

Structural transformation gradually closes off policy options for the agricultural sector. It is simply not possible to keep a third of the labor force employed growing rice and also have a modern industrial and service economy. Policymakers who fight the forces of structural transformation are fighting against the tide.

At the same time, structural transformation opens new options to policymakers to cope with the distributional consequences of structural transformation. Making rice "expensive" in East Asia, when it was 6.8% of the entire economy, would have been a fiscal fiasco. In 2007, doubling the price of rice in China to increase farm income may not be a wise economic policy, but with rice only 1.0% of the economy, it would no longer be fiscally impossible. The degrees of freedom for policy, wise or unwise, are clearly greater.

Thus, structural transformation is a two-edged sword. It reduces the importance of agriculture, and rice, to the overall economy. At the same time, it creates the resources to spend on making the rice sector successful in contributing to the goals society has held out for it for generations: food security for consumers and satisfactory income for producers.

Rice is still important on both counts in Asia, and it is rising, not falling, in importance in other parts of the world, especially Africa. In Bangladesh, for example, rice still provides about 70% of daily caloric intake, and the average for all of Asia is about 30%. In much of Asia, rice remains the food of the poor, so price volatility and market shortages have a direct impact on poverty.

In nearly all of Asia, rice farmers (whether part-time or full-time) are the single largest identifiable interest group, a fact not lost on political leaders. It is no accident that political elections in 2009 in India and Indonesia were won by leaders who provided sharply higher prices to rice farmers than in the world market in the years leading up to the world food crisis, and then were able to buffer domestic consumers from the panic-driven prices in world markets in early 2008. Stable rice prices, even at high levels to support farmers, seem to be a winning political strategy. Only a successful structural transformation makes such a strategy financially feasible, even if it remains economicallly inefficient. But, economists have not been very effective in designing efficient food price stablization programs that politicians need to stay in power.

The historical process of structural transformation may seem like a distant hope for the world's poor, who are mostly caught up in eking out a living day by day. Governments can do many things to give them more immediate hope, such as keeping staple foods cheap and accessible, connecting rural laborers to urban jobs, and providing adequate educational and health facilities in rural areas. But, to be sustained, all of these poverty actions depend fundamentally on a growing economy that successfully integrates the rural with urban sectors, and stimulates higher productivity in both. That is, the long-run success of poverty reduction hinges directly on a successful structural transformation.

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Notes

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Chapter 1.3

Asia's Green Revolution: past achievements and future challenges

Peter B.R. Hazell

Introduction

The Green Revolution (GR) helped transform Asia. It pulled the region back from the edge of an abyss of famine and led to regional food surpluses within 25 years. It lifted many people out of poverty, made important contributions to economic growth, and saved large areas of forest, wetlands, and other fragile lands from conversion to cropping. But the GR did not eradicate poverty and malnutrition. Although poverty shares fell, the number of poor people stubbornly persists at unacceptable levels. Widespread malnutrition, increasingly in the form of micronutrient deficiencies rather than calorie or protein shortages, also remains. The GR introduced new environmental problems of its own, especially those related to the poor management of irrigation water, fertilizers, and pesticides, and doubts have arisen about its sustainability. Critics of the GR have been quick to highlight these shortcomings, while the steady progress that has been made in tackling its shortcomings without sacrificing its high productivity levels are often underappreciated. This chapter seeks to rectify that balance. It also considers how the GR areas must evolve within the changing economic and social context within Asia and the re-emergence of global and regional concerns about food security.

The Asian Green Revolution

The GR was driven by a technology revolution, comprising a package of modern inputs—irrigation, improved seeds, fertilizers, and pesticides—that together dramatically increased crop yields. But its implementation also depended on strong public support for developing the technologies; building up the required infrastructure; ensuring that markets, finance, and input systems worked; and ensuring that farmers had adequate knowledge and economic incentive to adopt. Public interventions were especially crucial in Asia for ensuring that small farmers were not left behind, without which the GR would have been much less pro-poor.

The GR was a continuing process of change rather than a single event, and, even today, continuing improvements of cereal varieties and management practices help support and advance the high levels of productivity that were initially attained. Although the main thrust of the Asian GR occurred during 1965-90, it had many technology and policy antecedents in the rice revolution that began in Japan in the latter part of the 19th century and spread to Taiwan and Korea during the late 1920s and 1930s (Hayami and Ruttan 1985, Jirstrom 2005). The Asian GR began with improvements in rice and wheat, but high-yielding varieties were subsequently developed for a number of other major food crops, including maize, sorghum, and millet (Hazell 2008).

The key drivers of the GR are summarized below.

Irrigation

Asia was already investing heavily in irrigation prior to the GR and by 1970 around 25% of the agricultural land was already irrigated (Table 1). India had 10.4 million ha of canal-irrigated land in 1961 and 4.6 million ha of tank-irrigated land (Evenson et al 1999). Significant additional investments were made across Asia during the GR era, and the irrigated area grew from 25% to 33% of the agricultural area between 1970 and 1995 (Table 1).

Fertilizer

Like irrigation, fertilizer use across Asia was also growing prior to the GR. In 1970, 24 kg of plant nutrients were applied per hectare of agricultural land and average use grew rapidly to reach 171 kg/ha by 1995 (Table 1). These average fertilizer application rates mask considerable variation across crops and countries, and the levels used on irrigated rice and wheat typically reached much higher levels, for example,

Table 1. Indicators of input use during the Green Revolution in Asia.

Country	Irrigated area (% of agricultural area)		Fertilizer (kg/ha)		Annual growth rate in agricultural work force, 1967-95 (%/year)	Annual growth rate in agricultural land area, 1967-95 (%/year)
	1970	1995	1970	1995		
Bangladesh	11.6	37.6	15.7	135.5	1.05	–0.11
China	37.2	37.0	43.0	346.1	1.67	0.93
India	18.4	31.8	13.7	81.9	1.41	0.13
Indonesia	15.0	15.2	9.2	84.7	1.69	0.57
Korea, Rep. of	51.5	60.8	251.7	486.7	–2.22	–0.53
Malaysia	5.9	4.5	43.6	148.6	–0.23	2.07
Myanmar	8.0	15.4	2.1	16.9	1.85	–0.10
Nepal	5.9	29.8	2.7	31.6	2.06	1.63
Pakistan	67.0	79.6	14.6	116.1	2.09	0.38
Philippines	11.0	16.6	28.9	63.4	1.59	1.17
Sri Lanka	24.6	29.2	55.5	106.0	1.57	0.02
Thailand	14.2	22.7	5.9	76.5	1.67	1.61
Vietnam	16.0	29.6	50.7	214.3	1.86	0.38
Total	25.2	33.2	23.9	171.1	1.57	0.52

Source: Rosegrant and Hazell (2000, chapter 5).

about 200 kg/ha for rice in the Philippines and Vietnam by the mid-1990s (Otsuka and Estudillo 2009).

Improved seeds

Irrigation and fertilizer helped raise cereal yields, but their full impact was realized only after the development of high-yielding varieties (HYVs). Scientists sought to develop cereal varieties that were more responsive to plant nutrients, and had shorter and stiffer straw that would not fall over under the weight of heavier heads of grain. They also wanted tropical rice varieties that could mature more quickly and were insensitive to daylight length, thereby permitting more crops to be grown each year on the same land.

Building on rice breeding work undertaken in China, Japan, and Taiwan, the fledgling International Rice Research Institute (IRRI) in the Philippines developed semidwarf varieties that met most of these requirements and that could be grown under a wide range of conditions (Dalrymple 1986a). Similar achievements were made for wheat after Norman Borlaug (later awarded a Nobel Prize for his work) crossed Japanese semidwarf varieties with Mexican wheat varieties at what is now known as the International Maize and Wheat Improvement Center (CIMMYT) in Mexico (Dalrymple 1986b).

The adoption of HYVs occurred quickly (Table 2) and, by 1980, about 40% of the total cereal area in Asia was planted to modern varieties (World Bank 2007, p 52). This had increased to about 80% of the cropped area by 2000.

It should be noted that the HYVs were not developed overnight but were the product of a long and sustained research effort in Asia. Also, although many of the initial rice varieties released (e.g., IR5 and IR8) were successful in dramatically raising yield potential, they proved susceptible to a number of important pests and diseases and had cooking traits that were less appealing to consumers. Continuing investments in agricultural research led to the eventual development of second- and third-generation varieties that successfully combined high yield potential with good pest and disease resistance and preferred consumption traits (Otsuka and Estudillo 2009).

Public investment and policy support

The GR was more than a technology fix. It also required a supporting economic and policy environment. The need to educate farmers about the new technology, rapidly expand input delivery and credit systems, and increase processing, storage, trade, and marketing capacities to handle the surge in production was considered too large a challenge for the private sector on its own at the time, especially if small farmers were not to get left behind (Johnson et al 2003). It was also necessary to ensure that adoption was profitable for farmers. To achieve these ends, governments across Asia actively intervened in launching and implementing the GR. Some but not all public interventions were market mediated, and all were backed by substantial public investments in agricultural development (Djurfeldt and Jirstrom 2005).

Table 2. Percentage of harvested area under modern varieties in Asia.

Region	Rice	Wheat	Maize
South Asia			
1965	0.0	1.7	0.0
1970	10.2	39.6	17.1
1975	26.6	72.5	26.3
1980	36.3	78.2	34.4
1985	44.2	82.9	42.5
1990	52.6	87.3	47.1
1995	59.0	90.1	48.8
2000	71.0	94.5	53.5
East and Southeast Asia and Pacific			
1965	0.3	0.0	0.0
1970	9.7	0.0	16.2
1975	27.0	14.8	39.5
1980	40.9	27.5	61.7
1985	54.1	34.3	65.9
1990	63.5	58.7	73.0
1995	71.1	78.8	83.2
2000	80.5	89.1	89.6

Asian countries invested heavily to launch their GR, and continued to invest in agriculture to sustain the gains that were achieved. On average, Asian countries were spending 15.4% of their total government spending on agriculture by 1972 and they doubled the real value of their agricultural expenditure by 1985 (Table 3). The need to sustain investment levels is especially true of agricultural R&D, since there are long lead times in developing new products and farmers continually need new crop varieties and natural resource management (NRM) practices to stay ahead of evolving pests, environmental problems, and changing market demands.

Governments also shored up farm credit systems, subsidized key inputs—especially fertilizer, power, and water—and intervened in markets to ensure that farmers received adequate prices each year to make the technologies profitable. Many governments used their interventions to ensure that small farms did not get left behind. Substantial empirical evidence at the time showed that small farms were the more efficient producers in Asia and land reform and small farm development programs were implemented to create and support large numbers of small farms. Small farm–led agricultural growth proved to be not only more efficient but also more pro-poor, a win-win proposition for growth and poverty reduction (Pinstrup-Andersen and Hazell 1987, Djurfeldt et al 2005).

Table 3. Government expenditures on agriculture in Asian countries, 1985 PPP US$.

Country	Expenditure on agriculture (US$ million)					Share in total expenditure (%)				
	1972	1975	1980	1985	1990	1972	1975	1980	1985	1990
Bangladesh	2,358	528	1,187	1,749	1,269	23.2	11.0	12.3	15.7	5.4
China	11,595	17,843	24,542	21,113	28,229	8.5	12.1	12.4	8.3	8.9
India	15,491	13,680	22,877	30,549	39,109	22.1	9.7	14.6	12.6	11.5
Indonesia	1,436	3,020	5,026	4,351	6,157	7.6	9.8	9.6	6.8	7.6
Korea, Rep. of	537	993	1,129	2,244	4,332	3.8	6.3	4.1	5.8	6.9
Malaysia	348	458	1,264	1,581	1,830	4.0	4.2	7.2	7.9	5.7
Myanmar	272	219	655	874	296	12.5	13.3	23.6	24.5	9.3
Nepal	107	136	257	541	254	13.7	15.5	16.4	22.0	8.5
Pakistan	740	1,031	1,168	971	1,312	5.7	6.7	5.4	2.9	2.6
Philippines	416	1,145	729	604	1,409	4.5	9.0	5.3	5.7	6.0
Sri Lanka	627	449	589	2,124	614	12.3	9.0	5.7	20.0	5.8
Thailand	902	767	1,850	3,181	3,190	7.8	5.9	8.1	11.7	10.4
Total	34,828	40,269	61,273	70,151	88,001	15.4	10.5	12.4	10.9	9.6

Impacts

Impact on cereal yields and production

Average cereal yields grew impressively in Asia: wheat yields grew by 4.1% per year from 1965 to 1982 and rice yields by 2.5% per year (Table 4). The average rough rice yield rose from 2.03 t/ha in 1965 to 3.04 t/ha in 1982, and reached 4.2 t/ha by 2007 (IRRI World Rice Statistics 2009). Higher yields and profitability also led farmers to increase the area of rice and wheat they grew at the expense of other crops. Asia-wide, total cereal production grew by 3.57% per year over 1967-82, with average annual growth rates of 5.43%, 3.25%, and 4.62% for wheat, rice, and maize, respectively (Table 4). The growth rates were considerably higher in the bread-basket areas (e.g., Punjab and Haryana in India and Central Luzon in the Philippines), where the GR was launched. Cereal production in Asia more than doubled between 1970 and 1995, from 313 to 650 million tons per year. Asian rough rice production alone increased from 232.2 million tons in 1965 to 383.4 million tons in 1982 and to 590.1 million tons in 2007 (IRRI World Rice Statistics 2009). Although the population increased by 60%, the increase in food production was sufficient that, instead of widespread famine, cereal and calorie availability per person increased by nearly 30%, and wheat and rice became cheaper (ADB 2000, p 9). All these gains were achieved with a negligible growth per year in the total area planted to cereals.

Table 4. Growth rates (%/year) in cereal production in Asia, 1967-82.

Crop	Area	Yield	Production
Wheat	1.30	4.07	5.43
Maize	1.09	3.48	4.62
Rice	0.70	2.54	3.25
Other grains	–1.76	1.63	–0.15
All cereals	0.42	3.13	3.57

Source: Rosegrant and Hazell (2000, Table VI.3).

Impact on factor productivity and food prices

The GR not only increased yields, it also reduced the production costs per kg of cereal harvested. This enabled a win-win outcome in which cereal prices could decline to the benefit of consumers even while farmers and agricultural workers increased their earnings. This was possible because the HYVs shifted the yield function upward, giving higher returns to each unit of modern input—fertilizer, pesticides, and water—than earlier varieties, leading to higher returns to land and labor. For Asia as a whole, average land and labor productivity in agriculture grew by 3.03% and 1.53% per year, respectively, during 1967-82, and increased to 3.55% and 2.98% per year, respectively, during 1982-95 (Rosegrant and Hazell 2000). Total factor productivity

(TFP) also increased. Mittal and Kumar (2005) estimated that, in India, TFP in wheat production grew by 0.92% per year over 1972-95, and accounted for about 25% of the total growth in wheat production. The real cost of wheat production per kg declined by 2.20% per year over 1972-95. Similarly, Kumar and Jha (2005) estimated that TFP for rice production grew by 5.75% per year during 1971-80 in Haryana, by 2.38% in Punjab, and by 3.62% in Tamil Nadu—three of the leading GR states in India. The real costs of producing a kg of rice fell by 5.67%, 2.68%, and 4.55% per year, respectively, for the same states over the same period. In China, TFP for rice, wheat, and maize increased by 50–75% during the 1980s (Rozelle et al 2003).

Real cereal prices fell across Asia as the GR progressed. Of course, not all the price decline can be attributed to the Asian GR since there were also substantial increases in agricultural productivity in many other parts of the world. It is difficult to attribute the amount of the price decline to Asia's GR, but, in a relevant study, Evenson and Rosegrant (2003) used a global food model to simulate what would have happened to world cereal prices after 1965 if only the developed countries had experienced crop genetic improvements while the crop varieties in the developing world remained unchanged. They estimate that, by 2000, the rice price would have been 80–124% higher than the actual, and wheat prices would have been 29–61% higher.

Impact on production fluctuations

As noted earlier, the initial HYVs were dramatically successful in raising yields but they were also more vulnerable than traditional varieties to some important pest and weather stresses, thus increasing the risk of major yield and food production shortfalls in unfavorable years. Early work by Mehra (1981), among others, suggested that yield variability for cereals in India was increasing relative to increases in average yield (higher coefficients of variation) at the national level, raising the specter of a growing risk of national food shortages and high prices some years. Subsequent analysis showed that, at the plot level, many HYVs, particularly second-generation varieties, were no more risky than traditional varieties in terms of downside risk,[1] and that, although some crop yields measured at regional and national levels were becoming more variable (a bigger problem for maize and other rainfed cereals than irrigated wheat or rice), this was largely the result of more correlated or synchronized patterns of yield variation across space (Hazell 1982, 1989). Several scholars suggested that these changes might be attributable to the widespread adoption of input-intensive production methods that led to more synchronized adjustments in input use and hence yields in response to changes in market signals and weather events; shorter planting periods with the mechanization of land preparation leading to greater exposure to the same weather events; and the planting of large areas to the same or similar crop varieties with a common susceptibility to the same weather or pest risks (e.g., Hazell 1982, Ray 1983, Rao et al 1988). Later studies showed that rice and wheat yields generally became more stable in Asia in the 1990s, but the patterns for maize and coarse grains

[1]See relevant case study material in Anderson and Hazell (1989).

were more mixed, especially at country and subregional levels (Sharma et al 2006, Chand and Raju 2008, Gollin 2006, Larson et al 2004, Deb and Bantilan 2003, Singh and Byerlee 1990). Part of the gain in yield stability can be attributed to continuing investments in plant breeding to provide crop varieties that are more resistant to pest, disease, and climate risks (Smale et al 2009).

Indirect income and employment impacts

Productivity growth in agriculture can have far-reaching impacts on the productivity and growth of regional and national economies. Several growth linkages drive this relationship: benefits from lower food prices for workers, more abundant raw materials for agro-industry and export, release of labor and capital (in the form of rural savings and taxes) to the nonfarm sector, and increased rural demands for nonfood consumer goods and services, which in turn support growth in the service and manufacturing sectors.

The powerful economy-wide benefits emanating from the GR were amply demonstrated in India (Mellor 1976). The fact that India's national employment share in agriculture did not change for over a century until the full force of the GR was under way in the 1970s provided strong circumstantial evidence of the importance of agricultural growth as a motor for the Indian economy. This was also confirmed by Rangarajan (1982), who estimated that a one percentage point addition to the agricultural growth rate stimulated a 0.5% addition to the growth rate of industrial output, and a 0.7% addition to the growth rate of national income. Modeling studies using computable general equilibrium (CGE) models of other Asian country economies have also demonstrated the powerful growth impacts following productivity-enhancing investments in agriculture (e.g., Adelman 1984, Dorosh et al 2003).

Regional growth linkage studies have also shown strong multiplier impacts from agricultural growth on the rural nonfarm economy (Bell et al 1982, Hazell and Haggblade 1991, Hazell and Ramasamy 1991). The size of the multipliers varies depending on the method of analysis chosen, and for Asia they vary between US$0.30 and $0.85, that is, each dollar increase in agricultural income leads to an additional $0.30–0.85 increase in rural nonfarm earnings (Haggblade et al 2007). The multipliers tend to be larger in GR regions because of better infrastructure and market town development, greater use of purchased farm inputs, and higher per capita incomes and hence consumer spending power (Hazell and Haggblade 1991).

Impact on poverty

Reliable poverty data are not available for the early GR period, but, in 1975, nearly 60% of all Asians lived in $1/day poverty. This had declined to less than 33% by 1995 (Rosegrant and Hazell 2000). The absolute number of poor declined by 28%, from 1.15 billion in 1975 to 825 million in 1995. These reductions in poverty would have been even more impressive if the total population had not grown by 60% over the same period. Since the vast majority of the poor who were lifted out of poverty were rural and obtained important shares of their livelihood from agriculture and allied activities, then the GR was undoubtedly one of the forces accounting for that shift.

Given the complex causes underlying poverty and the diversity of livelihoods found amongst poor people, the relationship between the GR and poverty alleviation is necessarily complex and this has led to a large and contentious debate in the literature (Hazell and Haddad 2001, Hazell 2008). Much of the available impact literature focuses on the direct poverty impacts within adopting regions, while a smaller literature assesses the broader and indirect poverty impacts arising through food price changes and growth linkages.

Impacts within adopting regions. A number of village and household studies conducted soon after the release of GR technologies raised concern that large farms were the main beneficiaries of the technology and that poor farmers were either unaffected or made worse off (e.g., Farmer 1977). Later evidence showed mixed outcomes. Small farmers frequently did lag behind large farmers in adopting GR technologies, yet many of them eventually did adopt (Pinstrup-Andersen and Hazell 1987). Many small farmers also benefited from greater employment opportunities and higher wages in the agricultural and nonfarm sectors (Lipton with Longhurst 1989). In some cases, small farmers and landless laborers actually ended up gaining proportionally more income than larger farmers, resulting in a net improvement in the distribution of village income (e.g., Hazell and Ramasamy 1991, Maheshwari 1998, Thapa et al 1992).

Freebairn (1995) reviewed 307 published studies on the GR and performed a meta-analysis. The primary concern of nearly all the studies that he reviewed was on changes in inequality and income distribution rather than absolute poverty, the latter emerging as a more important issue in the 1990s. He found that 40% of the studies reviewed reported that income became more concentrated within adopting regions, 12% reported that it remained unchanged or improved, and 48% offered no conclusion. There were more favorable outcomes in the literature on Asia than elsewhere and, within the Asian literature, Asian authors gave more favorable conclusions than non-Asian authors. Freebairn also found that the later studies did not report more favorable outcomes than earlier studies, thereby casting some doubt on the proposition that small farmers did adopt but later than large farms. However, it should be noted that his analysis did not include repeat studies undertaken at the same sites over a longer period of time, such as Hazell and Ramasamy (1991), Hayami and Kikuchi (2000), and Jewitt and Baker (2007), all of whom found favorable longer-term impacts on inequality. Freebairn also found that micro-based case studies reported the most favorable outcomes, while macro-based essays reported the worst outcomes.

Walker (2000) argues that it may be easier to reduce poverty than inequality through technologically driven agricultural growth. More recent studies focusing directly on poverty confirm that improved technologies do impact favorably on many small farmers and landless workers, but the gains can often be too small to raise them above poverty thresholds (Hossain et al 2007, Mendola 2007). However, the poor can benefit in other ways, too. Hossain et al (2007) find that, in Bangladesh, the spread of HYV rice helped reduce the vulnerability of the poor by stabilizing employment earnings, reducing food prices and their seasonal fluctuations, and enhancing farmers' ability to cope with natural disasters. The use of participatory research methods in the selection of improved rice varieties in Uttar Pradesh, India, has been shown to empower women as decision makers in their farming and family roles as well as leading to greater adoption of improved varieties (Paris et al 2008).

Indirect impacts on poverty. A number of econometric studies that cover the GR era have used cross-country and/or time-series data to estimate the relationship between agricultural productivity growth and poverty. These studies generally find that agricultural productivity growth has high poverty reduction elasticities. Thirtle et al (2003) estimate that each 1% increase in crop productivity reduces the number of poor people by 0.48% in Asia. For India, Ravallion and Datt (1996) estimate that a 1% increase in agricultural value added per hectare leads to a 0.4% reduction in poverty in the short run and 1.9% in the long run, the latter arising through the indirect effects of lower food prices and higher wages. Fan et al (1999) estimate that each 1% increase in agricultural production in India reduces the number of rural poor by 0.24%. For Asia, these poverty elasticities are higher for agriculture than for other sectors of the economy (World Bank 2007, Hasan and Quibria 2004).

There is some evidence that the poverty elasticity of agricultural growth may be diminishing because the rural poor are becoming less dependent on agriculture. In Pakistan, for example, agricultural growth was associated with rapid reductions in rural poverty in the 1970s and 1980s, but the incidence of rural poverty hardly changed in the 1990s despite continuing agricultural growth (Dorosh et al 2003). This is partly because a growing share of the rural poor households (46% by 2001-02) had become disengaged from agriculture; even small farm households and landless agricultural worker households received about half their income from nonfarm sources.

Lower food prices and growth linkages to the nonfarm economy play an important role in most of the results cited above, and these benefit the urban poor as well as the rural poor (Fan 2007). These indirect impacts have often proved more powerful and positive than the direct poverty-reducing impacts of R&D investments (Hazell and Haddad 2001).

Interregional disparities. The GR began in the better regions with assured irrigation and although it subsequently spread to areas that depended more on rainfed crops, it did not benefit many of the poorest regions (Prahladachar 1983). The widening regional income gaps that resulted have been buffered to some extent by interregional migration. In India, the GR led to the seasonal migration of more than a million agricultural workers each year from the eastern states to Punjab and Haryana (Oberai and Singh 1980, Westley 1986). These numbers were tempered in later years as the GR technology eventually spilled over into eastern India in conjunction with the spread of tubewells. In a study of the impact of the GR in a sample of Asian villages, David and Otsuka (1994) asked whether regional labor markets were able to spread the benefits between adopting and nonadopting villages and found that seasonal migration did go some way to fulfilling that role. But, although migration can buffer widening income differentials between regions, it is rarely sufficient to avoid them. In India, for example, regional inequalities widened during the GR era (Galwani et al 2007), and the incidence of poverty remains high in many less-favored areas (Fan and Hazell 2001).

Impact on nutrition

The GR was very successful in increasing the per capita supply of food and reducing the prices of food staples in Asia. Making food staples more available and less costly has proved to be an important way through which poor people benefited (Rosegrant and Hazell 2000, Fan et al 1999, Fan 2007). Several micro-level studies from the Green Revolution era in Asia found that higher yields typically led to greater calorie and protein intake among rural households within adopting regions. For example, Pinstrup-Andersen and Jaramillo (1991) found that the spread of HYV rice in North Arcot District, southern India, led to substantial increases over a 10-year period in energy and protein consumption for farmers and landless workers. Ryan and Asokan (1977) also found net increases in protein and calorie availability as a result of GR wheat in the six major producing states of India, despite some reduction in the area of pulses grown.

More recently, concern has shifted from calorie and protein consumption to micronutrient deficiencies and broader nutritional well-being (Gillespie and Haddad 2003), and these pose more complex relationships with the GR. Declining cereal prices as a result of the GR were generally good for the poor as this amounts to an increase in their real income. In principle, the poor could use that increase in real income to increase their consumption of important staples, and also to purchase more diverse and nutritionally rich diets. However, a study of Bangladesh showed that a downward trend in the price of rice over the period 1973-75 to 1994-96 was accompanied by upward trends in the real prices of other foods that are richer in micronutrients, making these less accessible to the poor (Bouis 2000). Similar patterns were observed in India during the 1970s and 1980s when farmers diverted land away from pulses to wheat and rice, leading to sharp increases in the price of pulses and a drop in their per capita consumption (Kennedy and Bouis 1993, Kataki 2002).

Since then, there have been substantial changes in food intake patterns in rural Asia. In India, for example, the share of cereals in total food expenditure has declined while that of milk, meat, vegetables, and fruits has increased. Per capita consumption of cereals has also fallen in absolute terms (Nasurudeen et al 2006) and this is true for all income groups. However, since deficiencies in iron and the B-vitamins are common among the poor, the increases in micronutrient-rich foods must not always have been high enough to offset the decline from cereals. Other micronutrient deficiencies exist (e.g., vitamin C and D) but these are not related to reductions in cereal consumption.

As the GR unfolded, strategies were implemented to enhance the nutritional quality of the diets of the poor. These included

a) Improvements in the productivity of fruits, vegetables, livestock, and fish, in both home gardens and ponds for on-farm consumption and more generally to increase the marketed supplies of these nutrient-rich foods;
b) Promotion of food-crop biodiversity, especially traditional crops and cultivars that are rich in nutrients; and
c) Biofortification of major food staples.

Although improved technologies have helped enhance the nutritional value of diets, studies show that the most effective results are obtained when technology interventions are complemented by investments in nutrition education and health services and targeted in ways that empower women with additional spending power (Ali and Hau 2001, Berti et al 2004, Gillespie and Haddad 2003).

Returns to public investments

Given the key role that the public sector played in launching and sustaining the GR, it is important to ask whether the returns to its investments were justified.

Fan et al (2008) have estimated the returns to different types of public investment in agriculture in India over a four-decade period, beginning in the 1960s (Table 5). The marginal returns to these investments in terms of growth and poverty alleviation were very favorable in the early stages of the GR, and many, especially additional investments in rural roads and agricultural R&D, continued to give high returns through the 1990s. Although the returns to most input subsidies were initially

Table 5. Returns to agricultural growth and poverty reduction from investments in public goods and subsidies in different phases of India's Green Revolution.

Item	1960s	1970s	1980s	1990s
Returns in agricultural GDP (rupees per rupees spent)				
Road investment	8.79	3.80	3.03	3.17
Educational investment	5.97	7.80	3.88	1.53
Irrigation investment	2.65	2.10	3.61	1.41
Irrigation subsidies	2.24	1.22	2.38	ns[a]
Fertilizer subsidies	2.41	3.03	0.88	0.53
Power subsidies	1.18	0.95	1.66	0.58
Credit subsidies	3.86	1.68	5.20	0.89
Agricultural R&D	3.12	5.9	6.95	6.93
Decrease in the number of poor people per million rupees spent				
Road investment	1,272	1,346	295	335
Educational investment	411	469	447	109
Irrigation investment	182	125	197	67
Irrigation subsidies	149	68	113	ns
Fertilizer subsidies	166	181	48	24
Power subsidies	79	52	83	27
Credit subsidies	257	93	259	42
Agricultural R&D	207	326	345	323

[a]ns = nonsignificant.
Source: Fan et al (2008).

high, they declined sharply over time to the point where their benefit/cost ratios fell below one. This suggests that, although input subsidies played a useful role during the early stages of the GR in promoting small farm–led growth, the government should have had a more effective exit strategy once the subsidies had fulfilled their original purposes. Similar analysis for China and Thailand also shows high marginal returns to public investments in agricultural R&D, infrastructure, and education, and very favorable poverty impacts (Fan et al 2002, Fan and Rao 2008).

The high returns to agricultural research in India (Table 5) and for China in Fan et al (2002) are also supported by other studies that focus more narrowly on the returns to public investments in agricultural research. Evenson et al (1999) reviewed several impact studies from South Asia and found that the returns to national agricultural R&D investments exceeded 60% in all cases. At commodity levels, Alston et al (2000) reviewed 222 impact studies from Asia and found a median rate of return of 50%, higher than in other developing-country regions (Table 6).

Table 6. Rates of return to agricultural research.

Region	Number of estimates	Median rate of return (%/year)
Africa	188	34
Asia	222	50
Latin America	262	43
Middle East/North Africa	11	36
All developing countries	683	43
All developed countries	990	46

Source: Alston et al (2000).

Environmental challenges

Declining growth in yields and total factor productivity

The GR led to rapid growth in cereal yields and TFP, but more recently concerns have been growing about whether these high levels of productivity can be sustained.

Cereal yields have continued to rise on average across Asia since the GR era, but annual growth rates are slowing (Rosegrant and Hazell 2000, Hazell 2008). Moreover, TFP has been declining, meaning that farmers now have to use higher levels of inputs to obtain the same yields as before. This is confirmed by more careful, micro-based studies of wheat and rice yields in the Indo-Gangetic Plains (Murgai et al 2001, Ladha et al 2003, Cassman and Pingali 1993, Bhandari et al 2003), in India's major irrigated rice-growing states (Janaiah et al 2005), and in East Asia's rice bowls (Pingali et al 1997).

There are several possible reasons for this slowdown: displacement of cereals on better lands by more profitable crops such as groundnuts (Maheshwari 1998), diminishing returns to modern varieties when irrigation and fertilizer use are already high, and the fact that cereal prices have fallen relative to input costs, making additional intensification less profitable. But there are concerns that the slowdown also reflects a deteriorating crop-growing environment in intensive monocrop systems. Ali and Byerlee (2002) and Murgai et al (2001), for example, report deteriorating soil and water quality in the rice-wheat system of the Indo-Gangetic Plains, and Pingali et al (1997) report degradation of soils and buildup of toxins in intensive paddy systems in several Asian countries.

These problems are reflected in growing evidence on stagnating or even declining levels of total factor productivity in some highly intensive farming areas (e.g., Janaiah et al 2005). Ali and Byerlee (2002) have shown that degradation of soil and water are directly implicated in the slowing of TFP growth in the wheat-rice system of the Pakistan Punjab. Ladha et al (2003) examine data on long-term yield trials at multiple sites across South Asia and find stagnating or declining yield trends when input use is held constant. There is also concern that pest and disease resistance to modern pesticides now slows yield growth, and that breeders have largely exploited the yield potential of major GR crops.

Other environmental problems

The concerns about environmental stresses that may underlie the decline in growth rates of yields and total factor productivity also link to broader worries about the environmental sustainability of the Green Revolution. These wider issues include excessive and inappropriate use of fertilizers and pesticides that pollute waterways and kill beneficial insects and other wildlife, irrigation practices that lead to salt buildup and eventual abandonment of some of the best farming lands, increasing water scarcities in major river basins, and retreating groundwater levels in areas where more water is being pumped for irrigation than can be replenished (Hazell and Wood 2008). Some of these outcomes were inevitable as millions of largely illiterate farmers began to use modern inputs for the first time, but the problem was exacerbated by inadequate extension and training, an absence of effective regulation of water use and quality, and input pricing and subsidy policies that made modern inputs too cheap and encouraged excessive use.

Just how serious are the environmental problems associated with the GR and are they likely to undermine future food production and Asia's ability to feed itself? Measuring environmental impacts is difficult and, as a result, good empirical evidence is fragmentary, often subjective, and sometimes in direct contradiction with the overall trends in agricultural productivity. The best evidence relates to the degradation of irrigated land, increasing water scarcities, and the consequences of poor pest management practices.

Degradation of irrigated land. Evidence is growing that poor irrigation practices have led to significant waterlogging and salinization of irrigated land. The Comprehensive Assessment of Water Management in Agriculture (2007) estimates that nearly 40% of irrigated land in the dry areas of Asia is affected by salinization.

Water scarcity. Even more worrying for irrigated agriculture is the threat from the growing scarcity of fresh water in much of Asia. Many countries are approaching the point at which they can no longer afford to allocate two-thirds or more of their freshwater supplies to agriculture (Comprehensive Assessment of Water Management in Agriculture 2007). Most of the major river systems in Asia are already fully exploited at least part of the year, and the massive expansion of tubewell irrigation in South Asia has led to serious overdrawing of groundwater and falling water tables. In the Indian subcontinent, groundwater withdrawals have surged from less than 20 km^3 to more than 250 km^3 per year since the 1950s (Shah et al 2003). More than a fifth of groundwater aquifers are overexploited in Punjab, Haryana, Rajasthan, and Tamil Nadu and groundwater levels are falling (World Bank 2007, Postel 1993). Even as current water supplies are stretched, the demands for industry, urban household use, and environmental purposes are growing (Comprehensive Assessment of Water Management in Agriculture 2007, Rosegrant and Hazell 2000). It would seem that either Asian farmers must learn to use irrigation water more sparingly and more sustainably or the irrigated area will have to contract.

Pest management. Pest problems emerged as an important problem during the early GR era because many of the first HYVs released had poor resistance to some important pests. The problem was compounded by a shift to higher cropping intensities, monocropping, high fertilizer use (which creates dense, lush canopies in which pests can thrive), and the planting of large adjacent areas to similar varieties with a common susceptibility. Control was initially based on prophylactic chemical applications, driven by the calendar rather than incidence of pest attack. This approach disrupted the natural pest-predator balance, and led to a resurgence of pest populations that required even more pesticide applications to control. Problems were compounded by the buildup of pest resistance to the commonly used pesticides. As pesticide use increased, so did environmental and health problems. Rola and Pingali (1993) found that the health costs of pesticide use in rice reached the point at which they more than offset the economic benefits from pest control.

Efforts to achieve environmental sustainability

A growing awareness of these environmental problems has led a few GR critics to argue for a drastic reversal to the traditional technologies that dominated Asia before the GR (e.g., Shiva 1991, Nellithanam et al 1998). Such authors claim that yield growth rates were already high before the GR, but ignore the fact that this was largely the result of the spread of irrigation and fertilizers prior to the introduction of HYVs (Evenson et al 1999).

More generally, environmental concerns have led to a significant research response and a wider array of more sustainable technologies and farming practices. Some of these have been spearheaded by environmentally oriented NGOs that have contested the GR approach and undertaken research and extension activities of their own. Others have been developed by the national and international R&D systems for improving water, pest, and soil fertility management within intensive GR systems.

Some of the more important options that have been proposed for GR areas are discussed below.

Organic farming. Despite widespread publicity to the contrary, organic farming seems to have little to offer Asian farmers in GR areas who wish to continue to grow cereals. A recent study (Halberg et al 2006, p 40) concludes: "In high-yielding regions with near to economic optimal inputs of fertilizers and pesticides, the yields of organic farming are between 15–35% lower than present yields when comparing single crops, and possibly at the low end (35%) when including crop failures and the need for green manure in crop rotations."[2] This statement draws heavily on results from temperate countries, and crop losses could be even higher in tropical countries because of greater problems with pest and disease control. The same study concludes that organic farming has more to offer farmers in less-intensively farmed areas, such as many less-favored areas, or farmers who can benefit from price premiums for organically produced foods.

Badgley et al (2007) reviewed a large number of published studies comparing organic and conventional crops. Although they claim organically grown grains in developing countries have an average yield advantage of 57%, the more detailed results in their Table A1 tell a more nuanced story. Organically grown rice under irrigated conditions in Asian countries showed little if any yield gain. The best organic farming yield gains for Asia were obtained on upland rice and for maize and sorghum grown under rainfed conditions. These are areas where the conventionally grown crops usually receive limited nutrient inputs of any kind and hence have low yields.

The system of rice intensification (SRI). SRI was developed in the early1980s by Henri de Laulanie, a French missionary priest in Madagascar, as another alternative farming approach to the available GR rice technologies for small-scale farmers. It has since been widely promoted by a number of NGOs and the International Institute for Food, Agriculture, and Development (IIFAD) at Cornell University (http://ciifad.cornell.edu/sri). The main components of SRI are transplanting of young seedlings (8–15-day-old instead of 3–4-week-old plants) on small hills at much lower plant densities than usual, water management that keeps the soil moist rather than flooded, frequent weeding, and the use of high amounts of organic compost for fertilizer.

The claimed benefits include high yields even with traditional rice varieties; a significant savings in seed; little or no artificial fertilizer required; natural pest and disease control, eliminating the need for pesticides; reduced water use; and a flexible management that allows farmers to experiment and adapt the approach to their particular growing conditions. The approach is claimed to be environmentally sustainable and of particular relevance for poorer farmers who cannot afford modern inputs (Uphoff 2003).

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[2]Since organic agriculture involves greater generation of plant nutrients and organic matter within the landscape through crop rotations, fallows, green manures, and integration of livestock into cropping systems, each hectare of crop land harvested must be supported by additional land dedicated to these other needs. While it might well be possible to obtain comparable yields for some crops at the plot level, farm-level productivity can be considerably lower for organic farming. Yet, few studies of yield gains with organic farming seem to make this basic correction, leading to results that are inevitably biased in their favor.

Controversy has arisen because of claims of very high yields, sometimes exceeding the best experiment station yields for modern rice technologies. These high yields defy current understanding of the physiology of rice plant growth (Sheehy et al 2005). Proponents argue that there are strong synergies between the different management components of SRI that lead to strong root growth and higher yields, although these synergies remain poorly documented or understood (Mishra et al 2006).

Few of the yield claims have been verified under controlled experimental conditions. Trials undertaken at IRRI found no significant yield differences between SRI and conventional GR practices (quoted in Namara et al 2003). McDonald et al (2006) analyzed 40 sets of field trial results reported in the literature (five from Madagascar and 35 from 11 Asian countries) that compared SRI with "best management practices" appropriate to each site. Apart from the five Madagascar studies, which consistently showed higher yields with SRI, SRI led to an average yield loss of 11% in the other 35 studies, with a range of –61% to 22%.

Yield gains appear to be better in farm adoption studies. Farmers in Ratnapura and Kurunegala districts in Sri Lanka obtained 44% higher yields on average with SRI than with modern rice-farming methods (Namara et al 2003), and the average yield gain was 32% for farmers in Purila District of West Bengal in India (Sinha and Talati 2007). However, in both studies, SRI farmers showed considerable variation in the management methods they used, making it rather unclear as to what was being compared in the name of SRI. For example, many SRI farmers used inorganic fertilizer as well as compost, many grew both modern and traditional rice varieties, and their weeding and water management practices varied considerably.

SRI has yet to be widely adopted in any one country, although it can be found on small scales in many Asian countries.[3] Some of the reasons for poor uptake include the difficulties of controlling water with sufficient precision in many surface irrigation systems, the need for large amounts of compost, and the high labor demands for transplanting, hand weeding,[4] and generating and distributing compost. This is confirmed by available adoption studies. In Sri Lanka, adoption is positively related to family size (availability of labor) and ownership of animals (availability of manure) and is more common among rainfed than irrigated rice farmers (Namara et al 2003). Moser and Barrett (2003) obtained similar results in an adoption study in Madagascar. Moser and Barrett (2003), Namara et al (2003), and Sinha and Talati (2007) all found that adopters practice SRI only on small parts of their rice area despite higher returns to both land and labor, and they also found high rates of disadoption. This again suggests important constraints, possibly labor or suitability of available irrigation systems, as well as disappointing returns.

SRI is an interesting example of how knowledge- and labor-intensive management practices can help increase yields, reduce the use of water and agrochemicals, and improve soil management in intensive rice-farming systems. The key SRI man-

[3]See http://ciifad.cornell.edu/sri.

[4]The combination of wide spacing and reduced flooding creates ideal conditions for weed growth and hence the need for frequent weeding.

agement factors contributing to high yields appear to be an optimal planting layout, transplanting young seedlings, maintaining soil organic matter, and keeping the soil moist rather than flooded (Mishra et al 2006). If this is correct, then farmers might be able to capture part of the benefits of SRI while still retaining sufficient flexibility in their choice of crop variety, use of inorganic fertilizers, and weeding and pest management practices (e.g., use of herbicides and machines) to significantly reduce the overall labor requirements of SRI, thus perhaps enhancing its adoption. If not, then other knowledge-intensive management practices may offer comparable or better yield gains but with lower labor requirements.

Improved soil nutrient management. More eclectic approaches to making intensive GR farming sustainable seek to increase the efficiency of fertilizer use rather than displace it, thereby reducing production costs and environmental problems. Fertilizer efficiency can be improved through more precise matching of nutrients with plant needs during the growing season, and by switching to improved fertilizers such as controlled-release fertilizers and deep-placement technologies.

Site-specific nutrient management (SSNM) was developed by IRRI and its partners as a way of reducing fertilizer use, raising yields, and avoiding nitrate runoff and greenhouse gas emissions (especially nitrous oxide) from intensive rice paddies (Pampolino et al 2007). Developed in the mid-1990s, SSNM is a form of precision farming that aims to apply nutrients at optimal rates and times—taking into account other sources of nutrients in the field and the stage of plant growth—to achieve high rice yields and high efficiency of nutrient use by the crop. Farmers apply N several times over the growing period and use leaf color charts to determine how much N to apply at different stages. SSNM has been tested through on-farm trials in several Asian countries and IRRI has developed practical manuals and a Web site (www.irri.org/irrc/ssnm) to guide application.

The International Fertilizer Development Center (IFDC) has pioneered a urea deep placement (UDP) technology in rice. This involves the deep placement of urea in the form of supergranules or small briquettes into puddled soil shortly after transplanting rice (Bowen et al 2005). This method improves N-use efficiency by keeping most of the urea N in the soil close to the plant roots and out of the floodwater where it is susceptible to loss. On-farm trials in Bangladesh that compared UDP with standard urea broadcasting practices showed a 50–60% savings in urea use and yield increases of about 1 t/ha (Bowen et al 2005). The briquettes are also simple to make with small pressing machines, and can create additional local employment.

Low or zero tillage. In response to the declining growth in productivity of the rice-wheat farming system in the Indo-Gangetic Plains (IGP), zero tillage (ZT) has been adapted and introduced by the Rice-Wheat Consortium (RWC), a partnership of the Consultative Group on International Agricultural Research (CGIAR) centers and NARES from Bangladesh, India, Nepal, and Pakistan. The technology involves the direct planting of wheat after rice without any land preparation. Rice crop residues from the previous season are left on the ground as mulch. The wheat seed is typically inserted together with small amounts of fertilizer into slits made with a special tractor-drawn seed drill. The technology has many claimed advantages over conventional tillage in the rice-wheat system: it saves labor, fertilizer, and energy; minimizes planting delays between crops; conserves soil; reduces irrigation water needs; increases tolerance of drought; and reduces greenhouse gas emissions (Erenstein et al 2007, World Bank 2007). But it often requires some use of herbicides for general weed control. A key ingredient for its success has been the development of an appropriate seed drill for local conditions in the IGP.

Improved water management. Improved water management in Asian agriculture is essential for redressing growing water scarcities, improving water quality, and halting the degradation of additional irrigated land. This will require significant and complementary changes in policies, institutions, and water management technologies.

Technical research has shown the potential to increase yields in irrigated farming with substantial savings in water use (e.g., Mondal et al 1993, Guerra et al 1998). Realizing these gains is easiest when farmers have direct control over their water supplies, as with tubewell irrigation or small-scale farmer-managed irrigation schemes. For larger schemes, the best hope would seem to lie in the devolution of water management to local water user groups or associations.

Integrated pest management. As problems with the use of pesticides began to emerge, researchers gave greater attention to the development of crop varieties that have good resistance to important pests, and biological pest control methods. This led to the development of integrated pest management (IPM), an approach that integrates pest-resistant varieties, natural control mechanisms, and the judicious use of some pesticides (Waibel 1999).

Bangladesh has been in the forefront of IPM since 1981, and the government, with assistance from FAO, has aggressively promoted the approach through farmers' training schools. Sabur and Molla (2001) undertook a farm survey in 1997-98 and found that IPM farmers used less than half the amount of pesticides on rice as non-IPM farmers and had significantly higher gross income per hectare. Similar results were obtained by Susmita et al (2007) and by Rasul and Thapa (2003). Both studies found that IPM farmers saved significantly on costs (labor and pesticides). None of the studies report any significant productivity impact from the use of IPM, so the main economic benefits arise from lower costs. Farmers perceived fewer health problems with IPM in all three studies, though neither Susmita et al (2007) nor Rasul and Thapa (2003) could find statistical differences between the perceptions of adopting and nonadopting farmers. None of the studies provides any data on environmental impacts.

Despite the development of more sustainable technologies and farming practices for Asia's GR areas, their uptake and spread remains inadequate. There are several possible reasons for this, including high levels of knowledge and labor required for their practice; perverse incentives caused by input subsidies, insecure property rights, and the off-site nature of much of the environmental damage; and difficulties in organizing farmers to work collectively on remedial actions. These constraints require more calibrated policy responses, and developing these remains a major challenge for the future management of the GR areas.

Future challenges for Asian agriculture

The economic transformation that began to unroll in Asia as the GR advanced has also dramatically changed the economic context for agriculture. Sustained increases in average per capita incomes and urbanization led to diversification of national diets, with rapid growth in demand for many high-value foods and slow growth in demand for food staples. Agriculture's share in the gross domestic product (GDP) has declined steadily, but its share in the work force has declined more slowly, leading to widening productivity gaps between agricultural and nonagricultural workers. Rural populations have also continued to grow, along with the number of small and marginal farmers.

The global economic situation has also changed. With rapid growth in international agricultural trade, some Asian countries have become important exporters of cereals (including rice) and high-value agricultural products while others have become more dependent on imports to meet their national food needs. After more than three decades of declining world cereal prices, a global surge in demand for livestock feed and biofuels has tightened world cereal markets. The world food crisis of 2007-08 arose from an unhappy congruence of unfavorable weather events, low stocks, and speculative bubbles in commodity markets, but seems likely to mark the beginning of a new era in which food prices will remain higher than precrisis levels and become less stable (Piesse and Thirtle 2009, OECD-FAO 2007). Climate change will add to this uncertainty. National food security concerns are clearly back on the agenda for many Asian countries.

How should Asian agriculture adjust within this evolving economic and social landscape and what are the implications for policy, public investment, and agricultural research? Three major challenges will need to be addressed: (1) a continuing need to raise cereal yields to meet growing demand within the context of increasing water and land scarcities and climate change; (2) resolving remaining environmental problems with intensive farming by promoting more widespread adoption of sustainable farming practices—including adapting to climate change and contributing to reduced GHG emissions; and (3) responding to the changing needs of small farms and a growing agricultural work force.

Maintaining cereal yield growth

Demand for cereals will continue to grow in Asia to meet food, livestock feed, and bio-energy needs, and in total is projected to expand by at least 30% by 2050 just to keep up with population growth—which is expected to increase from 4 billion in 2008 to 5.25 billion by 2050 (FAO 2008). Since Asia accounts for 90% of global rice consumption and about 40% of global cereal consumption, any significant increase in Asia's import dependency would affect world prices as well as increase the region's vulnerability to world price shocks. Unless Asia can expand its cereal production roughly in line with demand, especially for rice, then real cereal prices are likely to increase. Although this would be good for farmers, it would have serious implications for the poor. Senauer and Sur (2001) estimate that a 20% increase in food prices would increase the number of undernourished in Asia by 158 million people.

The scope for increasing cereal production is constrained by worsening land and water scarcities and by rising energy and fertilizer prices. Each year, a significant amount of good agricultural land is being lost to urban, industrial, and infrastructure development, and most Asian countries have limited scope for bringing new land into cereal production except at high environmental cost. New sources of irrigation water are also limited, while nonagricultural uses of water for urban, industrial, and environmental purposes are growing rapidly. Climate change will exacerbate the problem by adversely affecting rice and wheat yields and increasing evapotranspiration (Rosegrant et al 2008). Continued strong growth in the production of high-value foods and biofuels is also adding to the competition with cereals for land and water (FAO 2008).

In this context, future increases in cereal production will have to come almost entirely from higher yields, with limited if any increase in the total amount of irrigation water used. Higher world energy prices will also mean higher fertilizer and mechanization costs for farmers, placing a greater premium on the types of management practices discussed in the section "Efforts to achieve environmental sustainability" that can increase yields while reducing the use of these inputs. Additional agricultural research will be the key to meeting these goals. Conventional agricultural research methods still offer much promise, as demonstrated by the recent release of hybrid rice, but as yield potentials become harder to raise, biotechnology will become more important. *Bt* rice has recently been released in China, and *Bt* maize may not be far behind. Some other promising possibilities include Golden Rice, which could reduce vitamin A deficiency among the poor, and C_4 rice, which promises higher yields with increased efficiency in the use of nitrogen and water (FAO 2008). Significant increases in water-use efficiency are possible in many GR areas but will require additional investments in irrigation infrastructure and difficult changes in the institutional and legal context in which water is supplied and used (Cai and Rosegrant 2007). In short, water users will need to have greater flexibility in making decisions regarding water use and water-pricing methods will need to send stronger signals about the real value of water.

As land and water prices increase, it may become more attractive to expand cereal production in many rainfed areas and to divert more irrigated lands to higher-value crops. However, although potential is significant for expanding rainfed cereal production in parts of Asia, a modeling study by Cai and Rosegrant (2007) suggests that there is also little scope for reducing the current irrigated cereal area if production is to keep pace with demand.

Resolving remaining environmental problems

A growing public awareness of the environmental problems associated with current patterns of agricultural intensification is increasing the demand for changes in land use and farming practices to reduce environmental damage and enhance the supply of environmental services to societies at large. Prominent among these services are cleaner water and air, protection of upper watersheds, reduced soil erosion and downstream flooding, biodiversity conservation, and carbon sequestration. For example, greater recognition of these needs has led China to introduce national laws requiring a "circular economy" approach to agriculture, whereby farmers and ancillary industries are expected to give more attention to reducing the use of external inputs, recycling waste products, and generally adopting practices that reduce off-site environmental damage (World Bank 2009, Huajun and Changbin 2006). However, the regulatory and market incentives needed to achieve this approach have yet to be implemented in China.

As seen earlier, agricultural research on sustainable farming technologies, water management, and NRM practices is already contributing to better on-farm resource management and sustainability, but there is scope for achieving broader environmental benefits by taking a more comprehensive view of the management of landscapes and watersheds. Given the off-site nature of many environmental costs and benefits, technological solutions alone are unlikely to suffice and there is a need for complementary policy, social, and institutional changes that can change incentives for farmers to adopt more desired technologies and management practices. Experience in today's high-income countries suggests that this will require comprehensive environmental regulations, which in turn require effective public institutions to monitor and enforce them. The emergence of markets and payment schemes for environmental services is also a promising possibility for Asia, though these may have less relevance for GR areas than for forest, upland, and mountain areas that protect watersheds, sequester large amounts of carbon, and harbor rich biodiversity.

Climate change will add to the challenge of improving the environmental management of GR areas. Adaptation strategies will be needed to cope with higher temperatures, higher evapotranspiration, and possibly reduced irrigation water supplies (Rosegrant et al 2008). Additional investments in infrastructure and agricultural R&D will again be important for meeting these challenges. Asia's GR areas are also a major contributor to global GHG emissions, predominantly through methane gas emissions from rice paddies and the CO_2 emissions associated with the production of nitrogen fertilizers. A key challenge will be to try to reduce these emissions without sacrificing the high cereal productivity that is needed. In many cases, it may not be possible to achieve these twin goals, and the GHG emissions associated with intensive farming in GR areas may simply have to be offset through carbon sequestration investments elsewhere. The emerging carbon offset markets could offer a viable instrument for this purpose, but a key question would be, Who is to pay for the carbon offset?

Managing the agricultural exit problem

As countries develop and per capita incomes rise, it is the normal historical pattern for workers to leave agriculture to take up nonagricultural jobs, and for farms to consolidate and become progressively larger, more mechanized, and fewer in number. Many small farms disappear and the small farms that do survive either shift into high-value production or become part-time. Without this transition, agricultural incomes are likely to fall seriously behind nonagricultural incomes, thus widening rural-urban inequalities. In today's industrial countries, the farm size transition occurred over many generations but a challenge facing many Asian countries today is that they are growing so fast that the farm size transition is not keeping pace. Indeed, the number of farms in developing Asia is still increasing and the average farm size is declining, despite a dramatic falloff in agriculture's share in total GDP (Headey et al 2010).

This too-slow a farm size transition is part of a larger problem of too-slow an exit of workers from the agricultural sector. Cross-country panel data suggest that most Asian countries not only have a higher agricultural labor share than should be expected given their current per capita GDP, but the rate of decline in recent years has also been abnormally slow (Headey et al 2010). Moreover, although the share of the labor force in Asian agriculture declined from 62.5% in 1990 to 56.2% in 2000, and is projected to fall to 50.5% by 2010 (IRRI World Rice Statistics 2009), most Asian countries have not yet reached a tipping point where the absolute number of agricultural workers begins to decline. In fact, the agricultural labor force increased from 893 million workers in 1990 to 970 million in 2000, and is projected to reach 1,022 million by 2010 (IRRI World Rice Statistics 2009).

Headey et al (2010) suggest that six factors are contributing to the too-slow exit rates from Asian agriculture. First, the GR catalyzed rapid growth in farm incomes and labor productivity, making it more attractive for workers to stay in agriculture. Second, the GR technologies were, initially at least, highly labor-intensive, creating many additional productive jobs. Third, the rural nonfarm economy (RNFE) grew rapidly in Asia—driven initially by increases in agricultural income, and dense population and settlement patterns—thus enabling many farm households to diversify their incomes while still relying on agricultural activities for their principal livelihood. This follows a pattern established in Japan and the Republic of Korea, where the number of small farms has remained stubbornly high despite both countries achieving industrialized status. Fourth, dense settlement patterns also meant that rural people had relatively good access to public services in rural areas and didn't need to migrate to cities to improve their basic quality of life. Fifth, many farmers cannot easily exit farming and it is instead their children who leave the farm. Farm exits simply take time—over several generations in today's industrial countries—and though the average age of Asian farmers is increasing, it is not doing so as fast as might be expected (Modrego et al 2006). Finally, in some countries, there have been barriers to rural-urban migration (e.g., China) that have made agricultural employment exits more difficult.

Unless resolved, the too-slow exit problem will result in widening income gaps between agricultural and nonagricultural workers, and between farmers and nonfarmers. This happened in Japan and the Republic of Korea during the later stages of their GR, and, because of the political power of rice farmers, led to the introduction of trade, price, and subsidy policies to support their incomes. If these kinds of policies are adopted more widely across developing Asia—and there are signs that this is already happening in India and China—then the fiscal and economic inefficiency costs of assisting some 400 million small farms could become immense. To avoid this prospect, Asian countries need to move on two fronts. One is to create more exit opportunities for small farmers and landless workers. The second is to exploit remaining opportunities for creating productive employment within the agricultural sector.

Asian farmers have already successfully diversified their incomes. On average, 51% of their total income is derived from nonfarm sources, of which 40% is from local nonfarm activity and 11% is from outside transfers and remittances (Reardon et al 2007, Otsuka et al 2009). This diversification has been possible because of rapid growth in the nonagricultural economy and because high rural population densities and dense infrastructure development have contributed to patterns of nonagricultural development that have been widely dispersed across both rural and urban areas. However, creating additional local and rural-urban migratory employment opportunities at the scale required remains a daunting challenge. India has failed to create enough nonagricultural jobs to keep pace with its growing work force despite its relatively fast growth since the early 1990s, and future prospects are bleak unless the agricultural sector can take up more of the slack (Bhalla and Hazell 2003). Even in high-growth China, creating enough nonagricultural jobs could be a daunting challenge given the ongoing shedding of public-sector labor, and the increasingly fast rate of rural-urban migration. Between 1999 and 2003, for example, the number of internal migrants in China roughly doubled, from 52 to 98 million, and China's 2000 census suggests annual migration rates of 8.5% of the work force, with roughly 30% heading to local townships, 30% to other counties in the same province, and 40% representing movement across provinces (Du et al 2005). Chinese policymakers may well face urban unemployment problems on a scale that would be relatively new to them, especially as the global financial crisis proceeds to hit China's export-oriented economy with unusual vigor.

The prospects for increasing productive employment in the agricultural sector are mixed. Within the cereal sector, the employment elasticity has fallen sharply since the GR era, and in India may now be close to zero (Bhalla and Hazell 2003). The decline has been particularly severe in irrigated GR areas due to the spread of mechanization and capital-intensive farming. More favorable employment prospects lie with high-value agriculture, which has seen very rapid growth in recent years in the production of livestock products, fruits, vegetables, and vegetable oils. Targeted polices should aim at helping more Asian smallholders compete and participate in these burgeoning markets. This will require investments in rural infrastructure and technology (roads, transport, electricity, improved varieties, disease control, etc.) and improvements in marketing and distribution systems for higher-value, perishable foods, including refrigeration, communications, food processing and storage systems, and food safety regulations (Rosegrant and Hazell 2000). In irrigated GR areas, this also requires a shift toward more flexible water control and management systems so that farmers can diversify their cropping patterns away from cereals.

One implication of the ongoing diversification of small farms is that commercial cereal production might increasingly be undertaken by larger farms. The relatively low returns per hectare from cereal production mean that only larger and more mechanized farms can make an acceptable living by today's standards from their production. A dualistic farm structure seems likely to emerge for cereal production, with larger farms providing most of the marketed surplus at low cost and many small and diversified farms producing cereals largely for own consumption. This pattern has already been emerging in some countries (e.g., Malaysia and Thailand), but its evolution in some Asian countries could be constrained by land tenure laws that limit land transfers (e.g., China) or the allowable farm size (e.g., India). To the extent that small farms are trapped in commercial cereal production, this can be expected to lead to higher cereal prices and growing pressure for income support policies.

Conclusions

The Green Revolution helped transform Asia. It pulled the region back from the edge of an abyss of famine and led to regional food surpluses within 25 years. It lifted many people out of poverty, made important contributions to economic growth, and saved large areas of forest, wetlands, and other fragile lands from conversion to cropping. Yet, poverty and malnutrition have not been eliminated, and widespread malnutrition, increasingly in the form of micronutrient deficiencies rather than calorie or protein shortages, remains. The GR introduced new environmental problems of its own, especially those related to the overuse and poor management of irrigation water, fertilizers, and pesticides. Doubts have arisen about the sustainability of intensively farmed systems, and off-site externalities such as water pollution, silting of rivers and waterways, and loss of biodiversity have imposed wider social costs. Much progress has been made in addressing these problems, but a substantial unfinished agenda remains.

Looking to the future, Asian farmers will come under additional pressure from more intense competition for land and water with urban and industrial uses, a more difficult growing environment because of climate change, greater public demand for better environmental management, and higher energy and fertilizer prices. At the same time, the number of small farmers and agricultural workers trying to earn a living in GR areas will remain stubbornly high, and rural-urban income gaps seem likely to widen. Yet, as cereal demand continues to grow, by at least 30% by 2050, it will be essential that yields continue to increase in GR areas. As with the earlier GR, this will require additional public investments in rural infrastructure, education, and agricultural R&D, but also significant changes in the institutions and legal arrangements for managing water and more comprehensive and effective environmental regulation. Interventions should also be targeted to help more small farmers diversify into higher-value production and nonfarm activities, and incentives improved for increasing the size of cereal farms.

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Chapter 1.4

Household income dynamics and changes in gender roles in rice farming

Sushil Pandey, Thelma Paris, and Humnath Bhandari

Introduction

Farmers in Asia grow rice and engage in various other income-generating farm and nonfarm activities. They produce many nonrice food and cash crops, and undertake fishing and livestock rearing. In addition, farm households have various nonfarm activities within their localities or outside. In this sense, the phrase "rice farmer" is a misnomer as farmers typically engage in multiple enterprises for their livelihoods. The relative importance of these various income components is determined by factors that include the overall biophysical characteristics of the farm; the farmers' endowment of land, labor, and capital, including human capital; the overall level of economic development; and the broader macroeconomic environment under which farming is undertaken. The income structure differs accordingly among households and across countries depending on these factors. It also differs over time as these determinants change temporally in the course of economic development.

The rice-growing areas of Asia show a lot of dynamism in their income structures with growth in the overall economy. This process started with the Green Revolution, which led to rapid increases in the productivity of the major staples rice and wheat. Rural income growth arising from the Green Revolution played a critical role in the overall economic growth of Asian countries (Hazell, this volume). More recently, further changes in rural income structures were spurred by several factors. In some areas, rice farmers are diversifying into other food crops and are also increasingly producing cash crops to meet demands for more diversified diets. There has been an expansion of nonfarm rural employment and accompanying increases in income. Farm size has been decreasing over time and this has diminished the relative importance of land as a leading source of income. There is considerable mobility of labor and migration of labor, especially of males, from rural to urban areas. The skill bases of rural societies in rice-growing areas are changing and diversifying. Similarly, the gender roles in rice farming and demographic profiles of farm households have been changing over time. Many of these changes are long-term in nature and will have far-reaching implications not only for crop production but also for the social organization of the farm household economy.

The main purpose of this chapter is to present some evidences of the nature of changes in income structures of rice-producing households in Asia. We focus on rice income and how it is affected by broader changes in the rural economy and changes in rural employment patterns. To do this, we rely mainly on farm-level data collected through various household-level surveys in South and Southeast Asian countries over time.[1] In addition, we examine the gender role in rice production and how it has been changing in response to occupational shifts and migration of the rural labor force. The implications of these broader changes for rice production systems of the future are discussed in the final section.

Dynamics of income/employment in the process of economic growth

It is well established that the share of agriculture in the gross domestic product declines in the process of economic growth and structural transformation (Timmer, this volume). The process of structural transformation entails a shift of resources from agriculture to other sectors of the economy. This means that the contribution of agriculture to both national production and employment decreases over time. This broader process, however, often results in changes in the relative importance of various agricultural activities, with the overall share of some components, such as the production of cereal crops, being affected more rapidly than others. These differential patterns of adjustment depend on several environmental, policy, and institutional factors that broadly determine the overall process of economic growth and structural transformation.

Although the income share of agriculture has declined quite rapidly with the process of income growth, the corresponding decline in the share of agricultural employment has been much more sluggish (Timmer, this volume). The share of agriculture in employment has been much higher than its share in income in most Asian countries, indicating that, at the aggregate level, labor is exiting agriculture slowly. Aside from likely data problems related to properly recording agricultural employment that may have inflated the estimates of agricultural employment, some of the major reasons for a slower exit are the expansion of the rural nonfarm economy, improvements in agricultural technologies that have facilitated diversification to labor-intensive high-value crops, and institutional barriers to exit in some cases (Headey et al 2010). In the context of Asian farms where rice production is a major activity, a slow labor exit from rural areas implies that rice production continues to generate a substantial amount of employment. For example, labor use in rice production in Asia varies from 15 person-days/ha/crop to 200 person-days/ha/crop, depending on the yield and degree of mechanization of farm operations. These figures imply the equivalent of 2–27 billion labor days of employment in rice production alone—quite a substantial amount of direct employment of agricultural labor force in the production of a single crop.

[1]We do not seek to explain the factors that contribute to the broader changes in income structure outside rice farming such as expansion of nonfarm rural employment, diversification to high-value crops, growth in migration, and increases in income from remittances. There have been several major analytical contributions to these in the literature (Otsuka et al 2009, Haggblade et al 2007). Broader changes in income aggregates that take place in the course of structural change have been discussed elsewhere (Timmer, this volume; Hazell, this volume).

How important is rice in the total household income of farmers?

At the household level, the process of structural transformation is seen in cross-sectional data across countries in the form of differential share of agricultural income in total household income (Fig. 1). The share of rice income in total income of rural households similarly varies across countries. Overall, the contribution of rice to the total household income of farmers who grow rice is less than 50% in the major rice-producing countries (and states) in South and Southeast Asia. In several cases, this share is below 20% (Table 1). At the national level, the actual share varies depending on the agro-climatic conditions, diversification of agriculture, and the overall level of economic growth. Local factors such as field type (upland/lowland, irrigated/rainfed) and household-specific factors assume importance in explaining the variation among households.

The share of rice in total farm household income is not only low but also has decreased over time with economic growth (Fig. 2). For example, in approximately 20 years' time span between 1985 and 2004, the share of rice in total farm income almost halved in the Philippines and in Bangladesh. Clearly, the importance of rice as a source of income and livelihood is less now than it was 20 years ago. At the broad aggregate level, other livelihood options have expanded over time and have gained in importance. This broad aggregate picture, however, masks variations across specific production environments where growth in such alternative livelihood options has varied for several reasons.

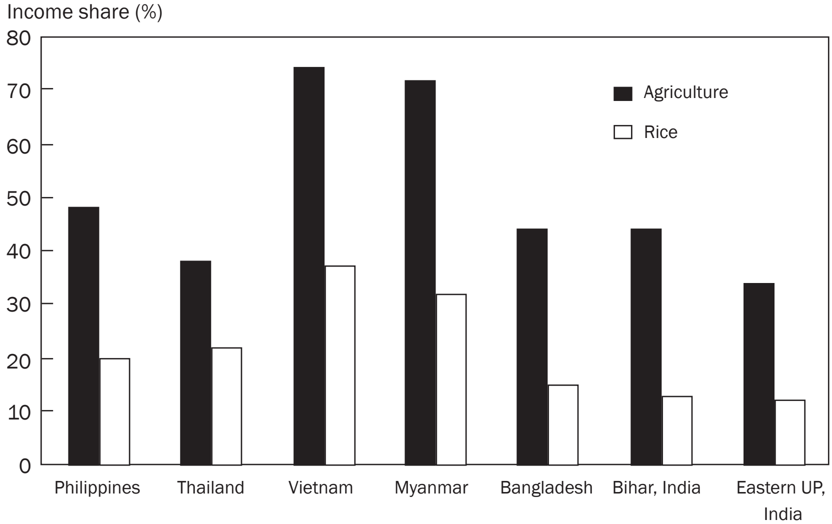

Fig. 1. Share of rice and agricultural income in total household income in Asia, 2004. Source: Hossain (2006).

Table 1. Percentage share of income from different sources.[a]

Country/state	Rice	Nonrice	Other sources	Nonfarm
India (eastern Uttar Pradesh)	14	26	8	52
India (Orissa)	19	8	6	67
Bangladesh	15	11	18	56
Nepal (Terai, Banke)	24	35	7	34
Philippines	27	3	2	68
Thailand (northeast)	15	25	7	53
Vietnam (Mekong Delta)	43	19	3	35

[a]Nonrice crops include crops other than rice, other sources include livestock plus off-farm wage labor, while income from nonfarm activities also includes remittances.
Source: Eastern Uttar Pradesh: Paris et al (2008).
Philippines, Thailand, and Vietnam: Paris and Rubzen (2008).
Orissa and Nepal: household survey for STRASA, IRRI (2008).
Bangladesh: Hossain and Bayes (2009).

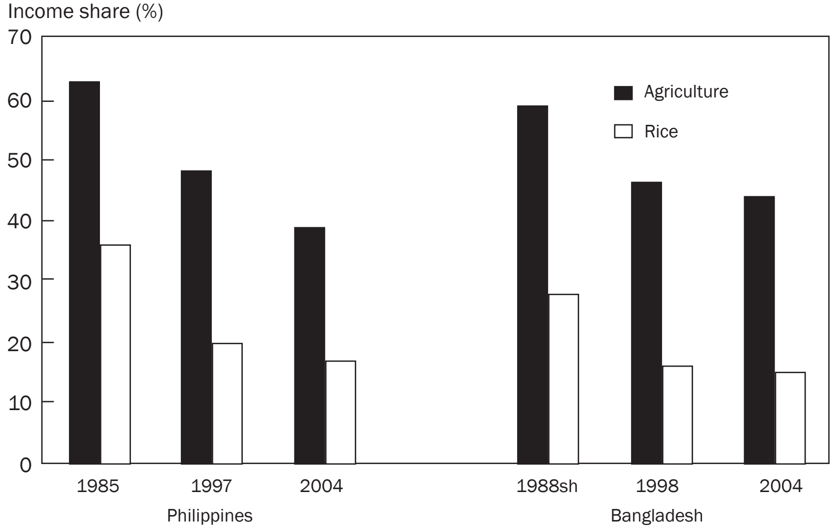

Fig. 2. Changes in rice and agricultural income in Asia, 1985 and 2004. Source: Hossain (2006).

Crop and income diversification

Together with the decrease in the share of rice in total income, the income shares of nonrice agriculture and nonfarm activities have increased. The nonrice components include other cereals (mainly wheat and maize) and higher-value crops such as oilseeds, vegetables, dairy products, and meat that have high income elasticities of demand. The aggregate demand for such products has risen with the growth in per capita income.

A major driver of diversification of rice systems is improved access to markets and changing diets. Commercialization and diversification of agriculture have often occurred together in response to increased access to urban markets (Pingali et al 1997). The increasing link with the market has promoted diversification in many areas for generating cash income.

In monsoon Asia, rice still accounts for the major share of cropped area and this share has changed very little over time (Table 2). This is despite the fall in the income share of rice. Rice is mainly a wet-season crop best suited to flooded field conditions that typically occur in most of monsoon Asia. It is only during the dry season that opportunities for diversification are greater, especially under irrigated conditions. Farmers in these areas, especially those closer to urban centers, have diversified into high-value commodities that are supplied to urban markets. Income contributions from high-value nonrice crops grown during the dry season can be substantial even if their area share is relatively small.

In favorable irrigated areas, the productivity of rice increased rapidly in the course of the Green Revolution as farmers adopted improved high-yielding varieties and increased fertilizer applications. Not only did the net returns per unit area increase substantially in the wake of the Green Revolution but farmers were also able to grow two or even three rice crops per year on the same piece of land, thus substantially boosting household income. This initially made rice production economically very attractive relative to other rural enterprises. Over time, the increased income from rice production facilitated the development of other rural enterprises through both forward

Table 2. Percentage share of rice in total cropped area in selected Asian countries.

Country	1980	2000	2007
Bangladesh	75	75	75
China	25	19	18
India	24	25	23
Indonesia	42	37	45
Nepal	44	34	31
Philippines	27	32	32
Thailand	57	56	57
Vietnam	68	62	54

Data source: FAOSTAT.

and backward linkages with other sectors (Rosegrant and Hazell 2000). In addition, farmers re-invested a substantial amount of their income gains from rice production to educate their children, who were then able to get employment in higher-paying nonfarm jobs, thus leading to enterprise and income diversification at the household level while raising total household income (Otsuka et al 2009). In the course of these changes in irrigated areas, the share of rice income in household income has decreased over time (Fig. 3). The decrease has been more in countries where nonfarm income has increased substantially such as in the favorable areas of the Philippines and Thailand. For Bangladesh, where the increase in nonfarm income has been proportionately much less, rice still accounts for about a fifth of household income.

In the case of unfavorable rice-growing areas (i.e., rainfed), a similar trend is apparent (Fig. 4). These areas did not experience as rapid a growth in rice yield as in irrigated areas and the average yield in rainfed areas is still only about 60% of that in irrigated areas. Income growth in less-favored rainfed areas has been mainly from nonfarm sources as opportunities for agricultural diversification are more limited due to field hydrological constraints as nonrice crops are generally less suitable under waterlogged conditions.

Farmers in these rainfed areas have depended mostly on a more diverse set of activities for their livelihoods, including wage income from labor in local areas and beyond. This dependence on a more diverse set of activities for livelihoods is exemplified by the case of rainfed areas of Thailand (northeast Thailand). The income share of rice in northeast Thailand was a little over 50% during the 1980s but this share went down to less than 10% in early 2000 while the share of nonfarm income increased sharply (Fig. 4). The rapid expansion of the nonfarm sector generated much of the employment and income for farmers from these low-productivity rainfed areas. Comparing this with the situation in unfavorable areas of India, nonfarm income increased only slightly and the share of rice income decreased but still remained above 20% while the importance of nonrice agriculture increased.

Growth in the nonfarm rural economy

A major driver of income dynamics in rural areas now is the growth of the nonfarm rural economy (Haggblade et al 2007). This consists of economic activities that can be broadly categorized as retail trade, manufacturing, and services. Self-employment is the dominant form of employment in Asia although some wage employment also occurs, mainly in the services sector. In all rice-growing areas of Asia, there has been an expansion of such activities and they now contribute substantially to the household income of rice farmers (Table 3). The rising importance of nonfarm rural income among rice farmers indicates an important change in their livelihood strategies.

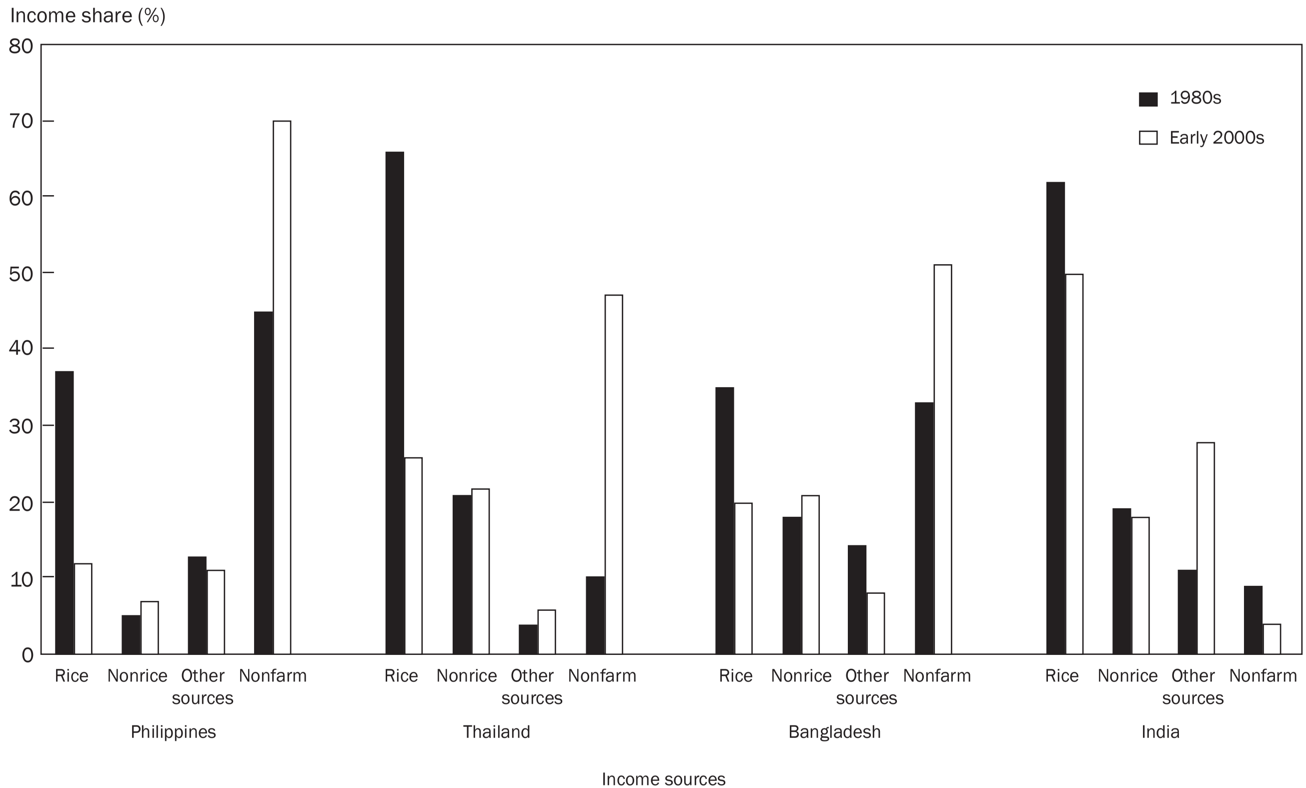

Fig. 3. Changes in composition of household income, favorable areas, Asia. Source: Otsuka et al (2009).

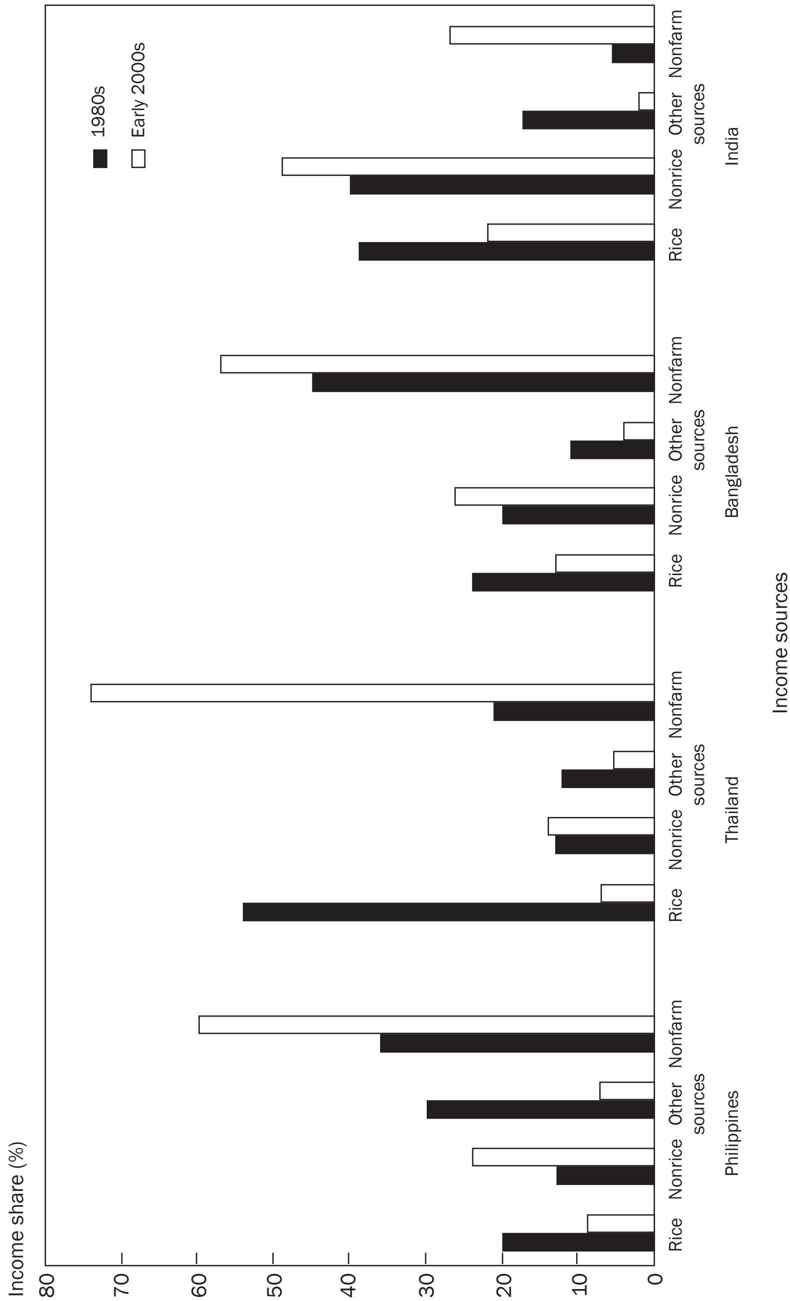

Fig. 4. Changes in composition of household income, unfavorable areas, Asia. Source: Otsuka et al (2009).

Table 3. Percentage share of the rural nonfarm (RNF) sector in total rural employment.

Country	Year	% RNF share
Bangladesh	2001	24
China	1999	26
India	1991	18
Indonesia	1995	37
Nepal	1981	6
Philippines	1980	25
Thailand	1996	50
Vietnam	1997	22

Source: Headey et al (2010).

Changes in farm size

Farm size in Asia has continued to decrease, with the number of farms increasing over time. The available information from panel data indicates this to be the case, generally (Table 4). High population pressure and limited exit of labor from rural areas partly aided by improved rice technologies and partly by the expansion of rural nonfarm employment are considered to be the major reasons for the continued pressure on land in Asia (Headey et al 2010).

Declining farm size means that the importance of land as a leading determinant of income decreases over time even after accounting for productivity gains in agriculture. A household has to pursue alternative income sources to prevent a decline in income when the land base is shrinking. This is obvious in the case of rice as indicated by the declining share of income from rice referred to earlier.

Changing gender roles in rice farming

Gender roles and responses are variable across and within cultures. Gender roles and gender relations within households are strongly influenced by social, cultural, and economic circumstances, family structure (nuclear or extended), and the degree of labor participation in the marketplace.

It is often assumed that household labor is homogeneous and thus freely substitutable across all household tasks, from home-based activities to off-farm wage employment. However, household members have certain degrees of specialization that result in differential time allocation to various tasks. Members receiving the highest wage offers and employment opportunities will naturally specialize in market-oriented work. Since men often receive better education and training, they develop more skills, receive higher wages, and have greater access to opportunities in the labor market than women. Women, on the other hand, tend to do more unpaid and home-based activities. If they are hired as seasonal agricultural laborers, they mostly receive lower wages

Table 4. Changes in average farm size and number of small farms.

Country	Census year	Average farm size (ha)	Number of small farms[a] (million)
India	1971	2.3	49.11
	1991	1.6	84.48
	1995-96	1.4	92.82
Bangladesh	1977	1.3	–
	1996	0.6	17.03
Nepal	1992	1.0	2.41
	2002	0.8	3.08
Pakistan	1971-73	5.3	1.06
	1989	3.8	2.40
	2000	3.1	3.81
Indonesia	1973	1.1	12.71
	1993	0.9	17.27
Philippines	1971	3.6	0.96
	1991	2.2	3.00
Viet Nam	2001	–	10.13
Lao PDR	1999	–	0.49
Myanmar	1993	–	1.66
Thailand	1978	3.6	–
	1993	2.9	1.86
China	1980	0.6	–
	1990	0.4	–
	1997	–	189.38
	1999	0.4	–
Total	circa 2000		340.53

[a]Small farms are defined as those with less than 2 ha, except in Thailand, where it is defined as farms less than 1.6 ha.
Source: Headey et al (2010).

than men do. Thus, the patterns of activities, resources, and participation in labor, income generation, and decision-making differ by gender (Feldstein et al 1989).

Aside from the important roles of poor women as unpaid workers and as agricultural wage laborers in rice production and processing, these women also provide labor in the production of nonrice crops and their marketing. They have an important role in the livestock sector (such as animal care, grazing, fodder collection, cleaning of the animal shed, processing of milk, and sale of livestock). Taking care of small animals (goats, pigs) and poultry provides a major source of independent income in times of distress for poor women. Rural women continue to have the primary responsibilities for domestic activities, including the hard physical tasks of water, fuel, and fodder collection and gathering wild foods.

Trends in gender composition of the economically active agricultural labor force

Important changes are taking place in the gender composition of agricultural labor with its continuing exit from agriculture. The growth rate of agricultural labor has decreased over time, with even the absolute number of the labor force decreasing in some countries (Fig. 5). In Thailand, the absolute number of agricultural labor started to decrease in the early 1990s and, after a stagnant period following the economic crisis of 1997, the exit of labor accelerated from 2006. The absolute number began to decrease in China in 2006 and more recently (in 2009) in Bangladesh. In other major rice-growing countries of Asia, the agricultural labor force is increasing but the growth rate has slowed considerably. These trends are projected to continue into the future.

In terms of gender composition, the female:male agricultural labor ratio is increasing in Bangladesh, India, and Indonesia, indicating that the relative share of women in agricultural labor is increasing over time (Table 5). For example, Bangladesh used to have 74 female agricultural laborers for each 100 male laborers in 1980 but this ratio increased to 104 in 2010 and is projected to increase to 123 in 2020 as men migrate and exit from agriculture. This is a clear indication that the importance of female labor in agriculture is increasing over time in these countries. This is also a general pattern in other Asian countries, except in the Philippines, where the high incidence of migration of women from rural to urban areas and overseas is a historical phenomenon. In Thailand, there has also been a slightly faster exit of female labor than male labor and the same seems to apply to a lesser extent for Vietnam. According to International Labor Organization projections, these broader trends are likely to continue into the future (Table 5). These changes in gender composition clearly indicate that the relative share of female labor will increase in rice production in the future.

Women's labor contribution to rice production

Women contribute at least half of the total labor inputs in rice production in Asia. It takes 57 to 215 labor days per hectare to cultivate rainfed lowland rice in various parts of Asia—with the median value being 133 days per hectare (Table 6). The use of female labor is as much as 84% in some locations in eastern India. Traditionally, women's labor use in rice farming was concentrated in pulling seedlings from nurseries, transplanting, weeding, and harvesting. Women provide 50% to 100% of the total labor for these operations.

The overall use of female labor in rice production is substantial although the relative shares vary by country, agroecosystem, class/caste, and availability of male labor. Despite the multiplicity of the factors that influence women's contributions to

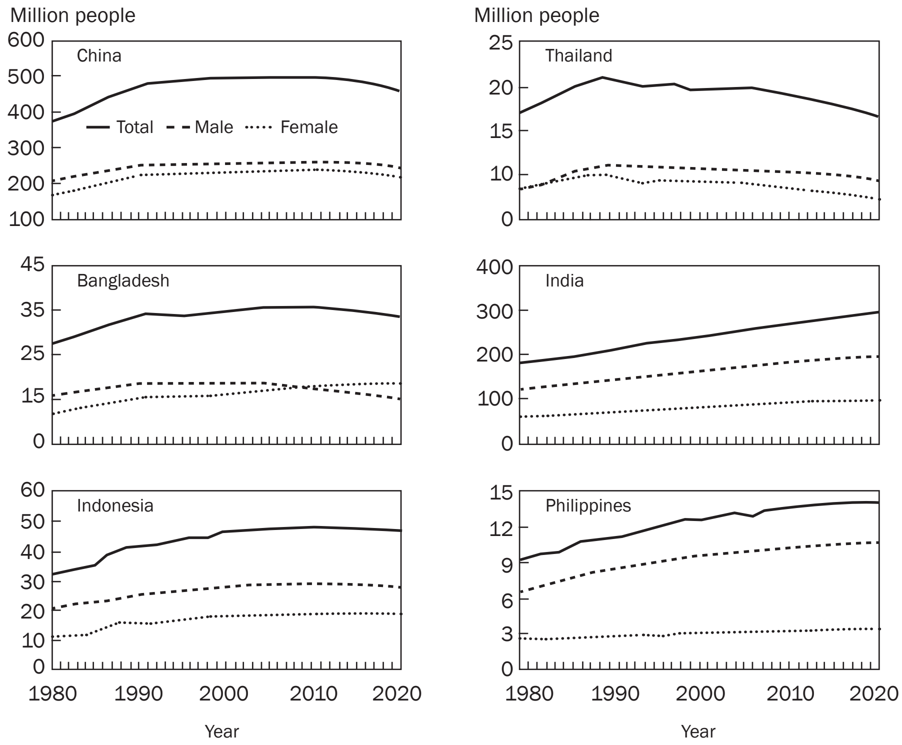

Fig. 5. Historical and projected trends in agricultural labor force and its gender composition. Data source: FAOSTAT.

Table 5. Trends in female:male ratio in agricultural labor force.

Country	Female:male ratio (%)				
	1980	1990	2000	2010	2020
Bangladesh	74	83	84	104	123
China	84	90	92	92	90
Philippines	38	32	32	32	32
Indonesia	48	48	48	48	49
India	51	65	64	65	68
Thailand	96	92	87	82	77
Vietnam	103	104	100	96	92

Data source: FAOSTAT, projections for 2010 and 2020 made by ILO.

Table 6. Labor inputs in rice production.

Location and type of crop	Labor	Labor contribution (%)	
	(days/ha/crop)	Male	Female
Northeast Thailand[a]			
Rainfed	90	59	41
Irrigated	80	60	40
Philippines[a]			
Rainfed	57	83	17
Irrigated	109	84	16
Southern Vietnam[b]			
Rainfed	134	35	65
Irrigated	95	58	42
Bangladesh[c]	140	80	20
Nepal[c]	215	48	52
India			
Assam[c]	80	47	54
Chhattisgarh[c]	100	58	42
Orissa[c]	105	61	39
West Bengal[c]	154	72	28
Uttar Pradesh[d]	193	26	74
Tamil Nadu[e]			
Rainfed	98	32	68
Irrigated	111	39	61

[a]Paris and Rubzen (2008) (2004 survey data). [b]Paris et al (2009) (2004 survey data). [c]Household survey for STRASA, IRRI (2008 survey data). [d]Paris et al (2008) (2005 survey data in rainfed area). [e]Cost of cultivation survey, Tamil Nadu University (2008 survey data).

rice production and processing, a simplified typology of rice production systems can be used to characterize the cross-sectional variations in women's labor use (Fig. 6).

Production systems tend to be subsistence-oriented when access to markets is limited and the production environment is less favorable (Type I). Remote upland areas and rainfed lowlands with low productivity typically have such characteristics. Rice is grown mainly for home consumption using mostly family labor and a limited amount of purchased inputs as the overall linkage with the nonfarm sector of the economy is relatively poorer. In such systems, men mainly do the power-intensive work such as land preparation, harvesting, and threshing. Women tend to specialize in transplanting, gap-filling, weeding, and some simple postharvest operations such as winnowing. Some of these broader labor-use patterns remain even in the more favorable irrigated areas where farming has not yet made a transition from a subsistence to commercialized mode of production (Type II).

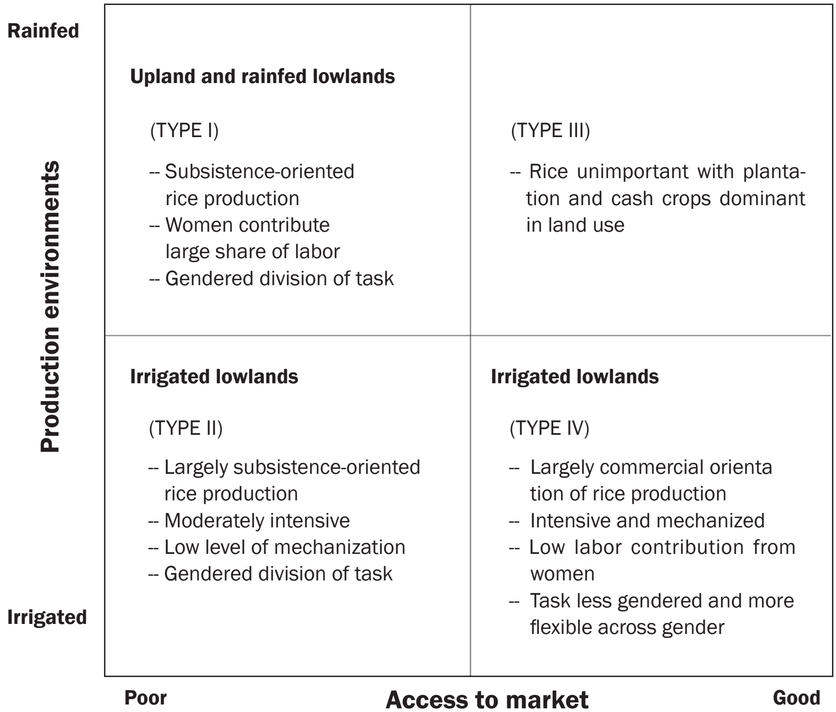

Fig. 6. Typology of rice production systems and corresponding gender roles.

Labor use in rice production is substantially different in intensive irrigated systems that are primarily market-oriented (Type IV). Rice production in such systems is largely mechanized, with labor use being limited to some basic critical activities for which it is more efficient to use labor (such as fertilization, spot weeding, etc.). Female labor use is lowest as women either engage in other more remunerative employment or, because of social customs, limit their work to homesteads.

Examples of these patterns are illustrated using recent data from eastern India, Nepal, and southern Vietnam (Table 6). In Nepal, female labor participation is higher in the mid-hills (Type I systems) than in the lowlands (Type II or IV). In contrast, the total labor use in intensive irrigated areas of Punjab (Type IV) is minimal due to mechanization and women are mostly engaged in other activities, including housework.

Major drivers of transitions in women's labor participation in rice production and processing

The typology can also be used to describe transitions in production systems and subsequent labor use. In Type I systems, increasing linkage with markets leads to transitions in labor-use patterns typical of Type IV, in which labor use in rice production is reduced overall. In addition, increasing linkage with urban labor markets changes the gender composition of total labor use, with women initially substituting for male labor that increasingly takes up employment in the nonfarm sector. Such a process leads to women taking on the task that traditionally belonged to men and making the traditional gendered division of labor less distinct. Over time, labor-saving innovations and mechanization are adopted in response to rising scarcity of labor and this results in a reduction in women's labor use as well.

The major drivers of transitions in labor use of women in rice production and processing include the extent of male migration, spread of labor-saving technologies and mechanization, and social and cultural norms regarding female labor. We now turn to these to discuss how gender roles undergo transitions in response to these factors and the potential consequences of such transitions for women's welfare.

Migration of male labor

Male labor is migrating from rural to urban areas in many rice-growing areas (Paris and Rubzen 2008, Paris et al 2005). As a result of male out-migration, the gender division of labor in rice farming has undergone important changes and is becoming more flexible. In Vietnam, particularly in the north, women are now in charge of tasks such as land preparation, spraying of chemicals, fertilizer application, and marketing that were traditionally in the male domain. This means that women are increasingly taking the decision-making roles in relation to overall crop management that were formerly taken by men. This can lead to an efficiency loss if women do not have adequate skills in crop management (Paris et al. 2005). The trend is different in the Philippines, where women (mothers and daughters) migrate more than men.

The adoption of labor-saving technologies and mechanization

A shift from traditional labor-intensive transplanting to direct seeding is taking place in Asian agriculture mainly in response to rising labor scarcity and the availability of improved methods for weed control (Pandey and Velasco 2002). This shift will have a direct impact on women's labor use in rice production as women traditionally supplied most of the transplanting labor. The impact will depend on whether transplanting is done mainly by family labor or by hired labor.

The shift to direct seeding will remove the drudgery and backbreaking burden of transplanting if the task is performed by female family labor. But, if transplanting is done by hiring women laborers, the shift to direct seeding will deprive them of a source of income. For example, the spread of direct seeding using mechanical row seeders in Vietnam resulted in a loss in income for hired female laborers who used to carry out transplanting (Paris and Chi 2005). The same reasoning holds for improved weed control technologies that require less manual weeding, depending on whether the female labor displaced is hired or family labor. Whether or not these adverse effects on poor wage earners are of a short-term nature will depend on the growth in other employment opportunities for absorbing the displaced labor.

Technologies that eliminate one rice operation and save labor also change the gender specificity of tasks, leading to labor substitution or flexibility in gender roles, particularly in the Philippines, Vietnam, and Thailand, where social and cultural norms are not as rigid as in South Asian countries. Tisch and Paris (1994) found that gender roles did not seem to be fixed, with men and women swapping their tasks when technologies such as direct seeding made it easier for them to do so. The adoption of direct seeding freed up women's labor traditionally tied up in transplanting for other economic tasks and men also provided some additional labor, such as for weed control to substitute for women's labor. Similarly, considerable flexibility was observed in irrigated rice farming in southern Vietnam in relation to traditionally gender-specific tasks such as irrigating the field and spraying chemicals (fertilizer and pesticides) aside from carrying rice seedlings from seedbeds to main fields for transplanting, purchasing, and transporting farm inputs and marketing of rice (Paris and Rubzen 2008).

Mechanization will likewise have different consequences for the employment and income of men and women. For example, the major rice-growing states of Punjab and Haryana in India have low labor use as mechanization is high. As a result, women have largely withdrawn from field activities in rice production. Men, who mostly manage and hire mechanical services for land preparation, harvesting, and threshing, however, are continuing their roles in rice production. Thus, the relative roles of male versus female labor have undergone changes because of the adoption of mechanization.

Social norms and economic incentives

Social norms and economic incentives are fundamental factors that influence women's participation in labor in agriculture, either as unpaid workers or as hired casual agricultural laborers. For example, there are regions in India where the caste system prevents women from participating in field work even on their own farms. This is the case, for example, in Bhitarkanik, in the state of Orissa in the eastern region. Under rigid caste codes, women from upper castes are not allowed to be seen outside their houses. On the other hand, women from lower castes are able to move outside their houses, work on their own farms, and work as wage laborers on others' farms. Religious concepts of purity and pollution prevent women from participating in the selection of paddy seeds and in storing them in the Kurichiyas community. Only occasionally, older women may become involved in seed selection. The influence of social norms on female family and hired labor participation is evident in rainfed lowland rice production in eastern India. Women among the upper caste do not work in their own fields but hire workers from the lower social class, mainly from the scheduled caste. Female family labor participation is highest among the backward caste and religious minority groups (Table 7). However, these social norms are breaking down because of economic necessities. Poor women who belong to upper caste households have now started to work on their farm in some parts of eastern India due to the labor shortage resulting from male out-migration and the steeply rising cost of hired labor.

Looking ahead: What are likely to be the future trends?

Some of the major trends in livelihood strategies, labor employment, and gender roles are the outcome of a broader process of economic growth and are likely to be reinforced in the future as agriculture undergoes structural transformation. These broader changes are, however, likely to take place at variable paces and compositions based on country-specific factors, policy environments, and social/cultural contexts. Here, we provide a summary of some of the likely major trends:

1. The importance of rice as a source of farm household income will decline over time because of crop diversification, the expansion of rural nonfarm employment, and increased labor employment in the broader nonfarm sector. Even if some specialization in rice production occurs in highly productive irrigated areas where double or even triple cropping of rice may be possible, the relative importance of income from rice at the household level will tend to decline as occupational diversification of family members takes place and more of the educated younger generation seeks employment in high-paying industrial and services sectors.
2. Farm size in densely populated Asia has been growing smaller over time. Until this trend slows and reverses, the importance of land as a leading determinant of income will decrease over time even after accounting for productivity gains in agriculture. Livelihood strategies of farm households will be increasingly based on nonland assets such as human capital.
3. With increasing out-migration of men and a decreasing male:female ratio of agricultural labor, the traditional gendered division of labor in rice production will become weaker, with women not only increasingly providing field labor for rice production but also taking on managerial and decision-making roles on the farm.

Table 7. Labor participation in rice production by caste and religious minorities in eastern Uttar Pradesh.

Item	Upper	Backward	Scheduled	Muslim	All
Total labor (days/ha)	114	134	135	152	127
Family labor (%)					
Male	2	28	7	18	16
Female		72		82	38
Hired labor (%)					
Male	9		4		4
Female	89		88		42
Family + hired labor (%)					
Male	11	28	11	18	20
Female	89	72	88	82	80

Source: Baseline survey on rural households 2004-05, IRRI.

Implications

Diversification of livelihood strategies of farmers in rice-growing areas of Asia and changes in gender roles that are expected to continue have important implications for the future of rice farming. Being a staple food of Asia, rice is bound to remain important for the household food security of Asian farm households. However, the decreasing importance of rice as a source of household income for most farm households means that their decisions on rice production and the adoption of improved rice technologies are likely to be based more on the consideration of other livelihood options available to them and the opportunity costs involved.

An important implication for rice research is that, even in somewhat densely populated regions of Asia, labor productivity will be an important criterion for farmers' evaluation of technologies in rice production, not just land productivity and subsistence needs. Technologies that demand less labor and provide greater flexibility in the labor-use calendar will be more attractive to farmers as such technologies will reduce competition for labor use among the various economic activities available to farmers. Similarly, research aimed at overcoming cropping systems-level constraints that limit opportunities for crop and income diversification would have a high payoff.

In the context of changing gender roles, an obvious implication is to design strategies and programs to rapidly upgrade the skill and capacity of women to efficiently manage rice farms. An initial important step for this is to formulate gender-responsive policy reforms that will reduce gender inequities in access to knowledge, skills, and technologies. Obviously, addressing gender inequities in the social/cultural context of farming in Asia is a broader agenda that goes beyond agriculture and requires interventions in other sectors, including health and education.

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Chapter 1.5

Fostering a Green Revolution in rice: Can Africa replicate Asia's experience?

Donald F. Larson, Keijiro Otsuka, Kei Kajisa, Jonna Estudillo, and Aliou Diagne

Introduction

There are natural and compelling reasons to look at the role rice might play in an African Green Revolution and to draw comparisons with recent experiences in Asia. Very broadly, advances in agricultural productivity have been central to economic growth and the structural transformation of most countries, so it is sensible to look for evidence that this process has begun in Africa. Moreover, there is also good reason to believe that agriculture-led growth can be especially effective in reducing poverty in Africa. This is partly because the poor are disproportionately rural and dependent on agriculture for their livelihood.[1] But it is also the case that poor households, whether urban or rural, spend a large portion of their income on food. As a result, productivity gains in staple crops such as rice and an associated decline in the price of staple foods can bring about spectacular reductions in poverty. The consequences of Asia's Green Revolution are a recent and dramatic example.[2] What's more, the genesis of Asia's success occurred under conditions similar to those found in Africa today and was closely linked to the successful adoption of a handful of innovative technologies, the most important of which centered on rice.

During the course of Asia's Green Revolution, policymakers vigorously promoted new high-input technologies aimed at wheat, rice, and other crops grown on smallholder farms. To date, a focus on smallholders and more intensive staple crop technologies—mostly for maize and rice—has been a pillar of most African agricultural policies as well. Still, the sweeping gains in agricultural productivity and the virtuous structural transformation of national economies that characterized Asia's Green Revolution have yet to reach Africa. Instead, average cultivated land per worker has declined in sub-Saharan Africa by about 40% since the 1960s and valued added per worker now averages around 12% below 1980 levels (World Development Report 2008).

In this chapter, we look closely at the specific case of rice, which was so important to Asia's Green Revolution and for which already available technologies are promising for Africa. We look backward at the role rice has played in African diets and African agriculture during the last 50 years and forward to the potential role rice can play in bringing a Green Revolution to Africa. We draw on lessons from Asia and from Africa, and, in particular, from ongoing efforts by the International Rice Research Institute

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[1]According to the World Bank, more than 70% of the continent's poor people live in rural areas and depend on agriculture for their livelihood (World Development Report 2008).

[2]See Larson and Mundlak (1997), Mundlak et al (1999), and Otsuka et al (2009).

(IRRI) and Africa Rice Center (AfricaRice)[3] to promote the use of new rice varieties. Taken together, what we find suggests that the successful development and dissemination of rice technologies have an important role to play in bringing productivity gains to Africa and that there are already signs of success. At the same time, because rice plays a less central role in African diets and livelihoods and because of the geography of Africa, the consequences of success for incomes and poverty are likely to be less sweeping than in Asia. Even so, for some places and for many households in Africa, especially in West Africa, the gains from adopting more productive rice technologies will be substantive, and it is difficult to envision a successful path to an African Green Revolution that does not include rice.[4]

The early debate on Asia's Green Revolution

Before looking at the potential role for rice in an African Green Revolution, it is useful to revisit early discussion about the anticipated consequences of Asia's new agricultural technologies shortly after their introduction, since concerns discussed then touch on topics still relevant for Africa. Though strong links between the introduction of modern varieties of wheat and rice with poverty reduction would be later documented, there were early questions about whether the new production methods would benefit large and wealthy farmers rather than poorer smallholders and promote mechanization as a substitute for agricultural labor. Rather than reduce rural poverty, some economists predicted that the new varieties would lead to increased landlessness and falling rural wages.[5]

The new varieties that led Asia's Green Revolution were bred to work better with greater applications of fertilizer than traditional varieties and to work best on irrigated land (David and Otsuka 1994). This entailed greater costs at planting time and greater capital outlays. Uncertainty over the local performance of the new varieties added to the financial risk of up-front investments, especially in the face of weak input and insurance markets. All of this seemed to favor larger farmers with better access to capital and rich enough to take on additional risk. Still, early evidence suggested that the scale of production and the wealth of the household mattered less than was supposed. For example, Hazell and Ramasamy (1991) report on an early study by Barker and Herdt (1978) on the effects of the adoption of the new semidwarf rice and associated technology on income and employment, based on surveys conducted in 36 villages in India, Indonesia, Malaysia, Pakistan, the Philippines, and Thailand. The authors found that, while smallholders faced considerable hurdles in acquiring inputs and credit, the rates of adoption for the new varieties were similar, even in villages where there were large inequalities in the distribution of land. Bell et al (1982) studied the introduction of irrigation and high-yielding varieties of rice in Malaysia's

[3]Formerly known as WARDA, the West Africa Rice Development Association.

[4]This is not to minimize the importance of rice for food security for some regions and urban centers. See, for example, the discussion in Wodon et al (2008).

[5]Chapter 1 in Hazell and Ramasamy (1991) provides a useful perspective. See, in particular, Frankel (1971), Cleaver (1972), and Griffin (1974).

Mudha River region from 1967 to 1974 and found both an increase in mechanization and a large increase in the incomes of landless rice workers. Blyn (1983), using data from Punjab and Haryana, reported that, in practice, yields declined with farm size and that mechanization did not hamper rural wage income. Around the same time, a number of studies suggested that the indirect local effects of the Green Revolution on income and employment opportunities were large (Bell and Hazell 1980, Estudillo and Otsuka 1999) and an important element of overall economic growth (Johnston and Kilby 1975, Mellor 1976, Timmer 2000).

One of the lasting effects of gains in agricultural productivity in Asia and elsewhere has been a relatively steady decline in the price of food staples from the 1970s until recent times. Because of the inelastic demand for rice and wheat as well as the competitive nature of agricultural markets, there were concerns that the benefits of technology gains in agriculture would flow exclusively to consumers, adding further to the gap between agricultural and nonagricultural income (Quizón and Binswanger 1986). Nevertheless, early studies suggested that this was not the case and that significant income gains accrued to rural villages following the adoption of new varieties (Blyn 1983, Ahluwalia 1978, Pinstrup-Andersen and Hazell 1985, David and Otsuka 1994). Much of the early evidence was selective and not broadly representative of national economies, but, with time, and especially after the launch of representative living standards surveys by the World Bank in the 1980s, better measures of the broad and cumulative effects on poverty of improving agricultural productivity emerged. And, on balance, there is now strong evidence that gains in agricultural productivity, especially in combination with investments in education and infrastructure, are transformational elements of poverty reduction and economic growth and that advances in agricultural techniques have contributed significantly to rising farm incomes and reductions in rural and urban poverty.[6]

Eventually, Asia's Green Revolution came to encompasses technological innovations in a number of crops, but breakthroughs in wheat and rice served as catalysts and conduits for most of the benefits associated with Asia's Green Revolution.[7] And, with the Asian experience in mind, several authors have called for a similarly styled African Green Revolution based on smallholder agriculture, staple crops, and high-input technologies designed to substantively improve agricultural productivity.[8]

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[6]The literature is large, but, for a sampling of the contributions of agricultural productivity on growth and poverty reductions, see Thorbecke and Jung (1996), Datt and Ravallion (1998), Foster and Rosenzwieg (2004), Mundlak et al (2004), Chen and Ravallion (2004), Christiansen and Demery (2007), Gulati and Fan (2008), Bezemer and Headey (2008), Otsuka et al (2009), and Suryahadi et al. (2009). There is also a large literature about the consequences of the Green Revolution for caste, gender, and culture. See Samaddar and Das (2008) and references therein.

[7]The start of the Green Revolution is often set at 1966, when the first modern or high-yielding varieties of rice and wheat were introduced in developing countries, although a case could be made for an earlier start with the development of new wheat varieties in Mexico. For an early discussion of the Green Revolution, see Hayami (1971). Evenson and Gollin (1997) and Evenson (2004) provide later perspectives.

[8]See, for example, Mosley (2002), Evenson (2003), Evenson and Gollin (2003), Djurfeldt et al (2005), and Annan (2007).

Even when successful, the approach of expanding agricultural productivity by relying on input-intensive methods is not without problems. Many relate to the poor management of natural resources, especially water and soils, and to the human and environmental costs of mismanaged chemical inputs.[9] Nevertheless, there is evidence that input-intensive techniques can be effective in Africa, particularly in the case of rice, which we discuss below. More importantly, current less input-intensive practices appear unsustainable in Africa. This is because organic input use and low-input soil management practices are not widely practiced in Africa, with the consequence that nutrients are continually extracted from African soils to feed current crops.[10] In the specific case of upland rice, growing population pressure has also reduced the length of traditional fallowing periods, putting more pressure on soils and exacerbating competition from weeds (Johnson et al 1998).

Still, although chemical fertilizer will be needed to intensify agriculture in Africa, a combination of organic and inorganic inputs works best under a variety of circumstances since they fulfill different roles.[11] While fertilizers directly supply plant nutrients, organic inputs may especially contribute to building the soil organic matter pool and improving soil structure, often resulting in reduced losses and improved capture of fertilizer nutrients by the crop.

Table 1. The role of rice in Asian and African diets, selected years.

Item	1965	1975	1985	1995	2005
Africa average calories[a]	2,100	2,167	2,238	2,318	2,407
Share of average					
Rice	0.05	0.05	0.07	0.07	0.08
Maize	0.15	0.15	0.15	0.16	0.15
Roots	0.16	0.15	0.13	0.15	0.14
Asia average calories	1,977	2,049	2,360	2,595	2,649
Share of average					
Rice	0.39	0.37	0.36	0.31	0.30
Maize	0.02	0.03	0.02	0.03	0.02
Roots	0.08	0.08	0.04	0.04	0.04

[a]Average calories are calculated on estimates of available food supplies as kilocalories per capita per day (FAO 2010).

[9]See Pimentel and Pimentel (1990), Byerlee and Siddiq (1994), Huang et al (2008), and Klemick and Lichtenberg (2008), and references therein.

[10]Henao and Baanate (2006), reported in Morris et al (2007), estimate that 85% of African farmland suffers soil nutrient losses at a rate of 30 kg/year or greater.

[11]See, for example, discussions in Vanlauwe et al (2002).

Developments in Africa's rice economy

In Asia, the important role of rice in the diet and livelihoods of the poor provided a leverage that translated significant production gains into reductions in poverty. As shown in Table 1, rice, on average, accounted for more than a third of caloric intake in Asia during the early stages of Asia's Green Revolution, so that incomes were sensitive to improved supplies and declining real prices. In Africa, the story is different and rice is less central to diets and income. Consequently, a set of coordinated gains across rice, maize, and cassava is needed to generate the same welfare effects. Even so, rice is different from other African staples because of its growing importance. As can be seen in Table 1, the share of calories from rice in the African diet is growing, while the share of maize and tubers has been relatively constant. Figure 1 illustrates both points and also highlights regional differences within Africa. As can be seen in the figure, rice consumption is becoming increasingly important in West Africa, though the gap between the region and Asia is still large.

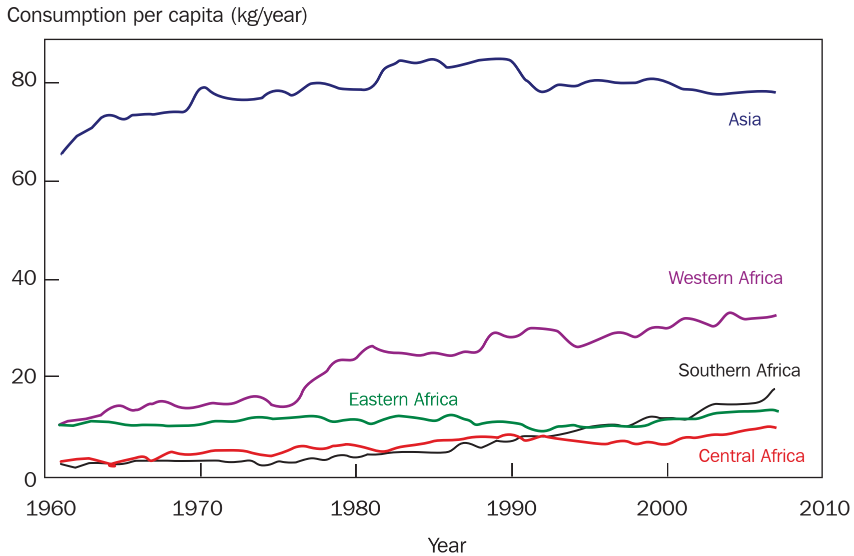

Fig. 1. Per capita rice consumption in Asia and regions of Africa. Source: FAO (2010).

Another significant feature of the African rice market is the growing importance of imported rice. As Figure 2 illustrates, rice imports have grown along with consumption and have accelerated during the last two decades. Contributing factors are urbanization and probably the steady decline in the international price of rice, which has fallen in real terms from the mid-1970s until recent times (Fig. 3).[12]

[12]The welfare gains from declining prices over time are mirrored by the costs of the recent spike in food prices. For example, Ivanic and Martin (2008) estimate that the most recent surge in food prices increased global poverty by 105 million people.

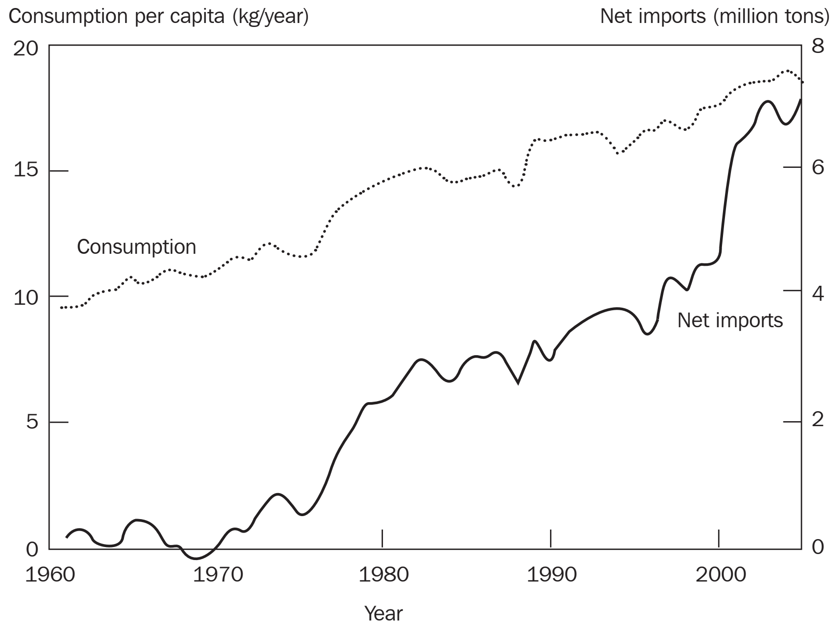

Fig. 2. Rice consumption and trade in Africa. Source: FAO (2010).

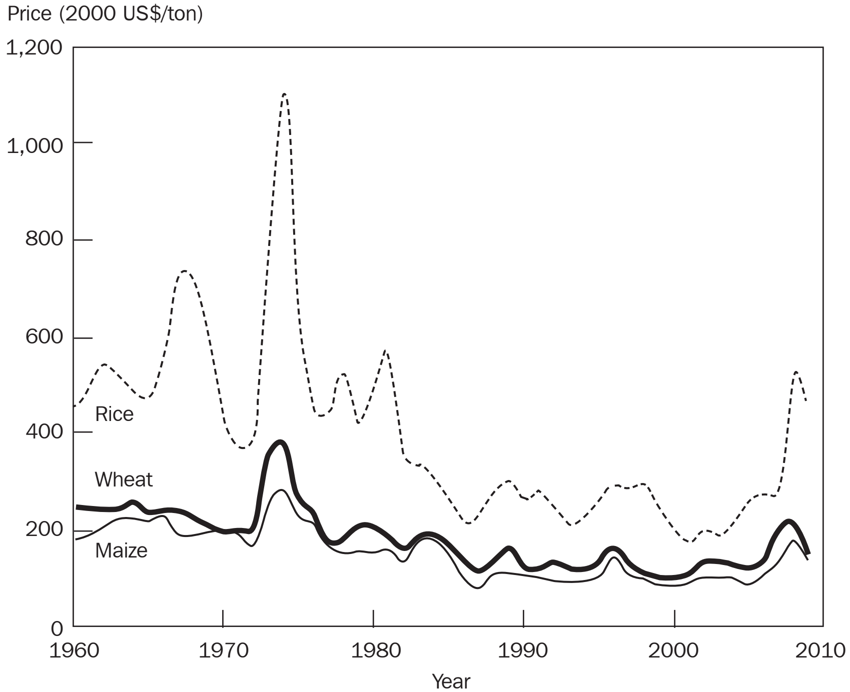

Fig. 3. Grain prices, 1960-2009. Source: World Bank (2010).

A broad shift in commodity policies is another factor that has influenced rice markets in Africa. By the late 1970s, many governments, including those in Africa, intervened significantly in food and other commodity markets. In the case of rice, state monopolies on trade, processing, and regulated prices were commonplace in Africa (Pearson et al 1981). For example, in Mali, a parastatal (Office des Produits Agricoles du Mali) held a legal monopoly on cereal marketing and processing for rice (McIntire 1981); in Senegal, the government limited trade, subsidized inputs, and set producer prices (Craven and Tuluy 1981). Beginning in the late 1980s and early 1990s, African governments began to dismantle internal marketing restrictions and lower trade barriers, a process driven by a desire to boost stagnating production, by fiscal necessity, and often supported by structural adjustment lending (Meerman 1997, Akiyama et al 2003).[13] As a consequence, world market conditions became increasingly important for African rice producers by the early 21st century.

The effects of the policies and the move to market-driven approaches are captured by Figure 4, which reports nominal assistance rates for eight African countries. The rates provide measures, in the case of a positive value, of the relative protection provided domestic farmers or, in the case of a negative value, the implicit tax trade policies impose on producers, which largely benefits domestic consumers. The figure shows that the net effects of rice policies in Africa have been inconsistent in the past decades, sometimes benefiting consumers, sometimes producers. However, in recent years, there has been a trend toward more neutral policies for which neither consumers nor farmers benefit at the expense of the other.

Despite policies that sometimes worked against farmers, rice production has grown steadily in Africa. However, the increase has come through expanded area. This differs from the experience in Asia and there is concern that further increases will be ultimately constrained by available land, or that additional gains in rice production will crowd out other crops. Figure 5 shows how the components of production have grown in Africa and in Asia during recent decades. In Africa, the area planted to rice has grown steadily, while there has been little land added to rice production in Asia during the last two decades. In contrast, rice yields have grown dramatically in Asia. In Africa, rice yields are much lower on an aggregate basis, but this is related to the fact that rice in Africa is still overwhelmingly grown under rainfed conditions. Moreover, the large differences in average yields between Africa and Asia belie the steady gains that have occurred in Africa.

Table 2 shows how production, area, and yields have changed for sub-Saharan Africa's largest producers between the 1980s and the first decade of the 21st century. In most cases, both area and yields have grown, although there are differences in the mix of area and yield growth. For example, although a significant portion of the growth in production in Nigeria is due to expanded area, cultivated land expanded little in Madagascar and most production gains came via better yields. Average yields improved significantly in Mali and Senegal as well.

[13]To continue the examples, Mali began restructuring its rice markets in the late 1980s and Senegal in 1995. Both received structural adjustment loans from the World Bank (Meerman 1997).

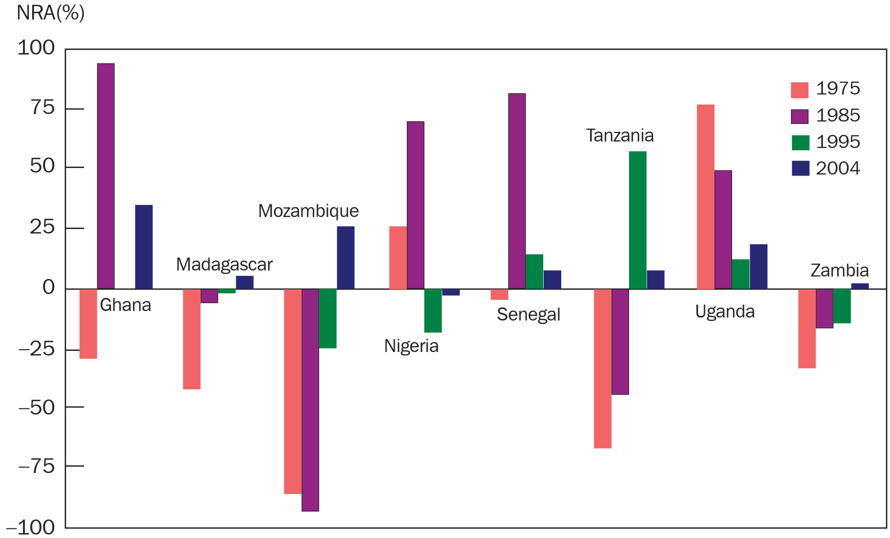

Fig. 4. Producer (nominal) rates of assistance (NRA) for rice in selected African countries, 1975 to 2004. Three-year averages of nominal rates of assistance centered on reporting year. The nominal rate of assistance is the percentage by which the domestic producer price for rice is above or below the border price. Source: Anderson and Valenzuela (2008).

Fig. 5. Rice area and yield in Africa and Asia. Source: FAO (2010).

Table 2. Production, area, and yield for selected African countries.

Country	Production (000 tons)			Harvested area (000 ha)			Yield (t/ha)		
	1960s	1980s	2000s	1960s	1980s	2000s	1960s	1980s	2000s
Nigeria	255.33	1,617.13	3,378.00	201.22	783.80	2,345.67	1.25	2.07	1.44
Madagascar	1,640.35	2,148.33	2,939.43	905.28	1,165.76	1,230.71	1.81	1.85	2.38
Guinea	252.38	587.79	1,240.68	148.22	343.94	701.43	1.70	1.71	1.76
Tanzania	119.34	446.95	1,094.09	104.44	291.21	621.90	1.16	1.51	1.76
Mali	164.37	204.54	937.24	167.02	178.63	415.59	1.00	1.13	2.25
Côte d'Ivoire	265.62	509.10	661.57	265.58	437.60	353.68	0.99	1.16	1.87
Sierra Leone	390.79	493.23	634.35	297.12	372.70	623.69	1.31	1.33	1.02
Congo, DR	95.17	296.50	319.13	123.20	363.60	422.69	0.77	0.82	0.75
Ghana	42.89	71.50	256.10	37.14	72.45	121.72	1.14	1.02	2.11
Senegal	108.38	129.49	227.37	82.00	71.03	88.56	1.30	1.82	2.53
Liberia	135.89	285.05	166.02	190.56	226.94	137.06	0.78	1.26	1.18
Mozambique	88.77	85.60	138.81	67.81	100.00	171.05	1.33	0.86	0.80
Uganda	4.17	22.10	137.33	3.80	17.00	96.56	1.18	1.30	1.43
Chad	31.60	36.63	120.91	27.41	31.58	94.54	1.16	1.11	1.27
Guinea-Bissau	45.28	94.37	104.10	52.33	78.14	69.41	0.94	1.40	1.49
Burkina Faso	34.73	40.02	101.15	41.97	25.52	49.71	0.85	1.62	2.03
Malawi	8.67	34.99	83.94	10.39	24.06	52.10	0.86	1.50	1.59
Mauritania	0.56	30.47	75.40	0.41	6.83	17.61	1.53	4.51	4.30
Togo	20.21	18.79	68.71	25.04	20.72	31.77	0.84	0.94	2.16
Benin	1.34	8.24	67.86	2.21	7.09	27.32	0.59	1.17	2.47

Table continued.

Table continued.

Niger	20.48	52.61	65.41	10.80	21.56	21.34	1.78	2.43	3.07
Burundi	2.77	20.00	64.35	1.31	6.76	19.58	2.26	2.92	3.28
Cameroon	12.97	70.18	52.65	12.56	18.51	35.72	1.00	3.96	1.64
Kenya	16.00	44.79	52.24	4.38	12.51	15.15	4.11	3.63	3.50
Central African Republic	6.59	13.40	37.07	7.22	10.56	18.94	0.91	1.30	1.94
Gambia	32.80	28.79	26.55	25.48	17.86	16.91	1.28	1.68	1.69
Sudan	1.34	3.49	19.75	1.54	4.19	6.43	0.97	0.93	2.99
Comoros	10.78	13.22	17.00	9.57	12.52	14.00	1.13	1.06	1.21
Zambia	0.07	8.12	15.08	0.17	8.53	12.03	0.40	0.92	1.26

Source: FAO.

Table 3. Proportion of rice land fully or partially irrigated in 2004.

Country	Percentage	Country	Percentage
Benin	2	Malawi	28
Burkina Faso	18	Mali	22
Burundi	21	Mauritania	100
Cameroon	95	Mozambique	2
Chad	9	Niger	80
Congo, DR	0	Nigeria	15
Gambia	7	Rwanda	8
Ghana	4	Senegal	50
Guinea	10	Sudan	75
Guinea-Bissau	1	Tanzania	27
Kenya	100	Togo	1
Liberia	2	Uganda	2
Madagascar	52		

Source: Balasubramanian et al (2007).

On the whole, very little of Africa's rice comes from irrigated plots—on average less than 20% in 2004 (Balasubramanian et al 2007). Table 3 reports the percentage of rice area partially or fully irrigated for sub-Saharan Africa's largest producers. With the exception of Senegal and Madagascar, the rice economies of most of the top rice production economies in sub-Saharan Africa are not centered on irrigation technologies. Nevertheless, as will be discussed in the next section, for large areas in Africa, water and land resources are available for expanding lowland production.

Natural resources and the potential for rice in Africa

In a recent article, Balasubramanian et al (2007) discuss the opportunities and constraints presented by sub-Saharan Africa's natural resource base. They argue convincingly that land and water resources suitable for rice are abundant in Africa. Estimates depend greatly on the definition of suitable. Still, the authors estimate that upwards of 240 million ha of agroclimatically suitable wetlands are available in Africa. They argue as well that the expansion of rice production need not compete with other food crops, since much of the low-lying wetlands suitable for rice during rainy seasons are inhospitable for other crops. Even so, only an estimated 3.5 million ha of wetlands are planted to rice in Africa.

The constraints on expanding rice production and productivity in Africa are numerous. Some have to do with abiotic risks, such as weather variability leading to droughts and flooding, extreme temperatures, and soil conditions related to erosion, salinity, low carbon content, and phosphorus fixation, which limit the efficacy of fertilizers. Other constraints are pests and diseases for the crop (weeds, blast, rice yellow mottle virus, and gall midge) and risks to draft animals and farming households, especially from water-borne diseases such as malaria and bilharzia. Additional constraints are economic, especially those related to poor transportation systems that adversely affect the relative farm-gate prices for inputs and marketed rice surpluses. The economic constraints are exacerbated by constrained credit and insurance markets and by low levels of education, which hamper information dissemination and extension efforts. In some cases, insecurity, the risk of predation, and weaknesses in the institutions charged with managing property rights and water resources also work against the uptake of more profitable and productive farming techniques. Moreover, because rice production can also take place in areas sensitive to the adverse effects of poorly managed production, the expansion of rice into wetlands can extract high environmental costs when the institutions that manage natural resources are weak.

Still, not all obstacles are present equally in all of the areas potentially suitable for rice production. In addition, advances in breeding and the dissemination of recently developed varieties can help with some of the biotic and abiotic challenges to rice in Africa and, by allowing rice plants to use nutrient and water resources more efficiently, address some of the economic hurdles as well.

In Africa, rice is grown in four ecosystems: upland (38% of planted area), rainfed wetland (33%), deepwater and mangrove swamps (9%), and irrigated wetland (20%) (Balasubramanian et al 2007). Wetlands can be subdivided into four categories: inland basins and low-lying drainage areas, river floodplains, inland valleys, and coastal wetlands. Among these, inland basins and inland valleys account for most of the area—about 193 million ha; the Congo basins are examples. Often, though well suited for rice, these areas can be remote from markets. River floodplains such as those adjacent to the Niger and the Zambezi, and coastal wetlands, including large river deltas and estuaries of the Gambia and Zaire, are part of this group and offer similar opportunities for rice cultivation. Total areas in these latter two subcategories amount to nearly 47 million ha and, as a group, are more accessible. Upland rice, also known as dryland rice, is dependent on rainfall and is grown on level or mildly sloping lands. Traditionally, upland rice is produced for home consumption in Africa and an examination of the area suitable for upland rice has not garnered the same attention as areas where water is more abundant. Still, Balasubramanian et al (2007) report that more than 2.7 million ha of land in Africa are planted to upland rice. Low productivity and profitability appear to be limiting factors, since upland rice requires moderate rainfall (annual totals of 0.9 to 2.0 m) and the shifting cultivation practices common in many of the areas where upland rice is currently grown suggest abundant land resources presently.

The relationships among modern rice varieties, ecosystems, and land scarcity are important for understanding the past evolution of Africa's rice sector and its future prospects. As Hossain (2006, 2007) points out, growing population pressure on food resources in Asia spurred the development of land-saving (higher-yielding) rice varieties and also led to the establishment of research institutions aimed at fostering further progress. One outcome was a set of technologies that disproportionately benefited water- and fertilizer-intensive rice. Looking at global growth rates across ecosystems, the author finds that yields for partially irrigated rice and irrigated rice grew 2.8% and 2.4% annually for 20 years between 1970 and 1990, whereas yields for rainfed upland rice increased at 0.9% annually for the same period. On balance, the new technologies for rice were less relevant for Africa, where investments in irrigation were lower and where high transport costs kept fertilizer prices high relative to the farm-gate price for rice. Importantly, the lack of substantive progress for nonirrigated rice left most African rice farmers without a strong alternative to traditional upland seeds and farming methods.

Still, as discussed, the use of Africa's abundant land resources is limited by a host of abiotic and biotic constraints and isolated by poor infrastructure. In addition, deteriorating water quality and declining soil fertility threaten some areas currently farmed. Moreover, in some cases, it will be important to preserve land otherwise suitable for rice, especially around estuaries, since these lands already provide valuable environmental services, for example, serving as buffers against storm surges and providing unique habitats for rare plants and animals.

For these reasons, the amount of new land available for expanding rice production is already limited in some countries and, with time, land frontiers in Africa will eventually close. It is perhaps telling that, while the average amount of arable and permanent crop land per capita of the agricultural population is significantly larger than in South Asia today, the amount is not so different from the late 1960s, when Asia's Green Revolution was getting under way (Fig. 6). Moreover, events in global markets may hasten this process, since there is evidence that gains from innovations of the type that fueled Asia's Green Revolution are slowing. For example, Hossain (2007) finds that, worldwide, annual yield gains for irrigated and partially irrigated rice from 1990 to 2005 slowed to 0.7% and 1.7%, while the growth in rainfed yields was largely unchanged. With new land suitable for rice limited elsewhere, the deceleration of yield growth among the world's largest rice producers and the growing demand for rice in and out of Africa will create new incentives for farmers in Africa to adopt the land-conserving farming practices common in Asia.

New Rice for Africa

The previous sections highlighted the current importance of lowland rice and the slow pace of improvement in rainfed yields worldwide. Overall, yield improvements can come about by improving the way current crop technologies are applied and through innovations in the form of new varieties. In the next section, we explore this first avenue for improving yields, looking especially at crop husbandry and water management practices commonly used in Asia that can be adapted for use in Africa. But, in this section, we turn our attention to a new family of rice varieties, initially developed for rainfed conditions.

This family of varieties is based on the successful crossing of an African rice (*Oryza glaberrima*) and Asian rice (*O. sativa*) and the term NERICA (New Rice for Africa) applies to the rice varieties that come out of this interspecific crossing of the

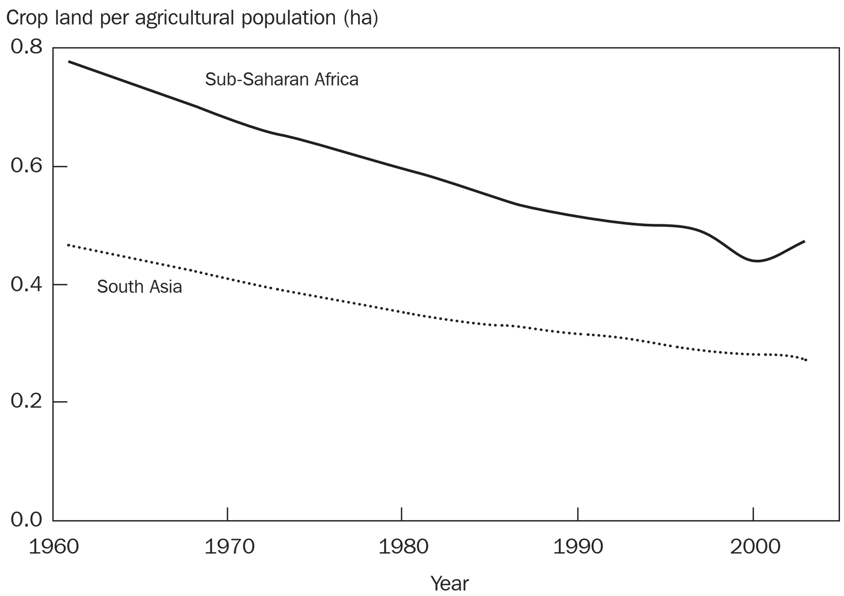

Fig. 6. Crop land per capita. This refers to crop land hectares divided by agricultural population, where agricultural population refers to all people dependent on agriculture, hunting, fishing, and forestry for their livelihood.
Source: 2008 World Development Report.

two distinct rice species.[14] Field tests suggest that the new varieties hold great promise with higher yield potential under a variety of soil and weather conditions, more protein, a shorter growing period, and a greater resistance to African pests and diseases.

NERICA varieties were developed at the main M'bé research center of the AfricaRice, through conventional crossbreeding. AfricaRice estimates that the initial research, which focused on upland rice, generated more than 3,000 interspecific siblings, encompassing a wide variety of attributes. By the close of 2005, 18 upland varieties (NERICA1–NERICA18) had been selected through participatory varietal selection (PVS) and on-farm trials by African National Agricultural Research and Extension Systems (NARES) for release in their countries. On-farm tests report rough rice yields in excess of 1 t/ha without fertilizer in rainfed areas and up to 5.7 t/ha when fertilizers are applied (Somado et al 2008). AfricaRice has also examined ratooning yields—that is, a secondary production obtained by leaving the lower part of the rice plant during harvesting. Based on field studies from Dévé, a savannah zone of Benin, Sanni et al (2009) report that ratooning yields ranged from 39% to 13%, potentially pushing the combined yields past 6 t/ha. Kouko et al (2006), reported in Somado et al (2008), found similar results from field tests in Kenya.

[14]This section draws on an informative NERICA compendium edited by Somado et al (2008).

The scope of the interspecific breeding program has grown substantially since 2000. Of particular interest is the creation of a set of NERICA lines suitable for irrigated areas and rainfed lowlands. Although the upland NERICAs are based on the upland strain of Asian rice (Japonica), the so-called NERICA-Ls are based on the lowland strain (Indica). Breeding efforts date from 2000, and research has focused on 60 progenies. By 2006, eight NERICA-Ls had been released for testing in farmers' fields in Burkina Faso, Cameroon, Kenya, Mali, Niger, Togo, and Sierra Leone (Somado et al 2008). The lowland NERICA varieties are expected to have a bigger impact than the upland NERICA, with rough rice yield potential of 6–7 t/ha. The results from a study conducted in the 2004 wet season in eight countries at 19 sites gave lowland NERICA yield ranging from 5 to 7 t/ha. NERICA L-9 and NERICA L-33 obtained the highest yield among the 37 selected varieties, with 7.2 t/ha and 7.1 t/ha, respectively (Sie et al 2008).

As discussed, in many places, upland rice is a crop grown to meet food needs and little is marketed. Consequently, markets for inputs and outputs are not necessarily well established and the full benefits of the new lines may go unrealized. An immediate problem is the supply of rice seeds. Private seed companies sell to a limited market in Africa. Further, in some cases, import policies aimed at safeguarding agriculture can also create hurdles to adequate seed supplies. As a result, farmers acquire most seed from informal sellers or produce the seed themselves. For NERICA varieties, farmers who have been trained properly can maintain the quality of their seed for extended periods, since NERICAs, like other rice varieties, are self-fertilizing. To fill the gap, AfricaRice has promoted community-based seed production systems in Benin, Gambia, Ghana, Guinea, Côte d'Ivoire, Mali, Nigeria, and Sierra Leone.

Early evidence from the first round of NERICAs suggests obstacles to the diffusion and adoption of the new technology among farmers and, consequently, adoption rates in terms of proportions of farmers and area planted.[15] For example, Diagne et al (2009) report adoption rates of 4% for Côte d'Ivoire in 2000, 20% for Guinea in 2001, 18% in Benin in 2004, and 40% in Gambia in 2006. In Nigeria, Spencer et al (2006) estimated that up to 30% of farmers in the state of Ekiti, Nigeria, cultivated NERICA varieties in 2005 and that 42% of farmers in Kaduna, Nigeria, grew NERICAs. Diagne suggests a range of social, economic, and institutional hurdles. Markets played a role; both land availability and participation in land markets boosted adoption. Programs that increased farmers' awareness about the characteristics of particular NERICA varieties proved key as well.

Still, even in places where NERICAs have been introduced, overwhelming evidence from the field of substantial yield benefits is slim. This point is emphasized by Orr et al (2008), who discuss the gap between the potential of NERICA varieties and evidence of their success. For example, the studies by Diagne cited earlier show mixed outcomes. On the one hand, an impact evaluation suggests that NERICA varieties generated significantly higher yields in Benin, but similarly structured evalu-

[15]By diffusion, we refer to the degree to which farmers have knowledge of NERICA technology and access to seed. These are the preconditions for adoption, that is, the farmers' choice to plant NERICA varieties.

ations provide no strong evidence of broad yield improvements in Côte d'Ivoire or Guinea. In Uganda, where rice is a relatively new crop, Kijima et al (2008, 2010) report favorable yield outcomes for some NERICA varieties. Moreover, consistent with evidence on yields, studies suggest consumption benefits in Benin (Adekambi et al 2007) and Uganda (Bergman-Lodin 2005, Kijima et al 2006). At the same time, a recent study by Kijima et al (2010) suggests that heterogeneous outcomes should be expected. Based on a panel of rice farmers in Uganda, their study suggests that differences related to climate and alternative income sources, as well as differences among farmers in their capacity to replicate seeds of NERICA varieties, can lead to different adoption outcomes.

Although there is an urgent need to increase the number of evaluations of the impact of NERICA varieties on yield, there are suggestions that evaluations should be broadened beyond measures of land productivity. Wopereis et al (2008) emphasize this point in their discussion of the role farmer preferences should play in the evaluation of new varieties. For example, Diagne suggests that the reason farmers might prefer NERICA varieties to traditional varieties with similar yields has to do with the shorter growing season for NERICAs. This characteristic reduces the risks associated with terminal droughts, saves on labor, and sometimes allows for a second rice crop. Because evaluations tend to focus on yield (land productivity) rather than labor or total factor productivity, the benefits of NERICAs go unmeasured under normal weather conditions. There is support for the latter view in a study by Dalton (2004), which suggests that the shorter growing cycle, rather than potential yield benefits, is NERICAs' most attractive feature.

Lessons from Asia

In this section, we turn to the prospects of expanding lowland rice in Africa, based on lessons from Asia's experiences. This is not to diminish the ample opportunities for learning from Africa's own experiences. As will be discussed later, sub-Saharan Africa has several examples of significant productivity gains and yields in Egypt are among the highest in the world. Still, Asia's successful Green Revolution is well established and well studied and this is helpful when considering Africa's future. It is also worth pointing out that the lessons from Asia mostly concern breakthroughs in irrigated and semi-irrigated lowland rice, so the lessons drawn here pertain to the particular places with conditions that are conducive to these rice production systems. Consequently, the degree to which Asia's technologies are directly transferable to Africa will be place-specific, although, as we argue below, the scope for transfer is large. Moreover, the scope for adaptation, that is, the scope for modifying Asian practices to suit African conditions, is larger still.[16]

The Green Revolution for rice in Asia started in 1966 when IRRI released IR8, the first modern variety of rice. Rice is the essential Green Revolution crop in Asia,

[16]Often, the difference has to do with water availability and water management practices. See, for example, the discussion in Wopereis and Defoer (2007).

and, although the Green Revolution in Africa may include more than one crop as none dominates, rice will be important for several reasons.[17] First, Asia has already accumulated a huge stock of scientific knowledge and useful production methods that could well serve Africa if selectively and appropriately adapted to its socioeconomic and agroecological environments. Second, as shown in Figure 2, there has been an increasing demand for rice but a low self-sufficiency ratio of only about 60%. Third, lowland rice varieties, which propelled and sustained the Asian Green Revolution, have exhibited high yield potential in lowland areas in sub-Saharan Africa, for example, a short-duration IRRI-bred variety was selected by AfricaRice breeders in the 1990s and is now widely grown in the Senegal River Valley. Fourth, and finally, a huge amount of farmlands are agroclimatically hospitable to rice production. As discussed, Balasubramanian et al (2007) estimate that upwards of 240 million ha of wetlands are available, which is 1.7 times more than the 142 million ha of rice area harvested in Asia in 2008 (FAOSTAT 2009).

Borlaug (2002) argues that Africa essentially needs a simple, effective farming system based on modern technology—chemical fertilizer, improved seeds bred for local conditions, and effective crop management practices. This is perhaps overly simplistic, since it fails to take into account the complexity of Africa's geography and rice production systems. Nevertheless, it does reflect a commonly held view that a "seed-fertilizer" approach is also appropriate for Africa. In turn, this makes Asia's stock of potentially profitable matured technologies especially relevant for Africa.

The Asian Green Revolution in rice did not happen overnight but was a long-term evolutionary process involving long and sustained efforts in rice research spanning more than four decades since 1966. The first generation of modern rice varieties (e.g., IR5 and IR8) were effective in dramatically increasing yield potential but were susceptible to various forms of pests and diseases. The second generation of modern rice (e.g., IR36) incorporated a wide spectrum of pest and disease resistance traits and early maturity period (Khush 1995). Resistant modern varieties (MVs) contributed significantly to the acceleration of yield growth by reducing yield variability, thereby increasing the expected yield, particularly during the dry season (Otsuka et al 1994). The shorter growth duration increases cropping intensity per year, which results in more harvests from a given plot of land each year (Barker et al 1985). The third generation of modern rice varieties (e.g., IR64) successfully combined high yield potential with pest and disease resistance and grain quality that are preferred by rice consumers. In more recent years, there have been efforts to use biotechnology in developing rice that is suitable to unfavorable environments (i.e., drought-prone rainfed lowland, upland, flood-prone, and tidal wetlands) for which the conventional breeding method has produced only a small number of rice varieties (Khush 1995).

There are already clear success stories on the use of Asian rice technology that indicate the possibility of inducing the evolutionary processes of a Green Revolution

[17]Although there have been attempts to disseminate high-yielding varieties of sorghum and millet, which also have relevance for Africa, these efforts were confined largely to some parts of India (Deb and Bantilan 2003).

in Africa. Average rough rice yields have improved dramatically in the Office du Niger in Mali and the Senegal River Valley in Senegal since the 1980s and now average 5 to 6 t/ha. And, *Oryza sativa* lowland rice grown in areas with a simple irrigation canal in Côte d'Ivoire yield an average of 3.6 t/ha while those varieties that were grown in areas without a canal have an average yield of 2.5 t/ha with minimum or even zero application of chemical fertilizer (Sakurai 2006). Kajisa and Payongayong (2008) demonstrate that yields of lowland rice can be potentially high (3.8 t/ha) in irrigated areas of Mozambique, where irrigation facilities are poorly maintained. Evidence from Uganda suggests that NERICA varieties could potentially increase the yield potential of upland fields from 1 t/ha to 2–3 t/ha (Kijima et al 2008). And, finally, a study in the Doho irrigation scheme in eastern Uganda reveals that rough rice yields are as high as 3 t/ha even without the application of chemical fertilizer and despite continuous double cropping of rice for the last few decades (Nakano 2008).

It is important to note that yields can be raised by improving simple water control and crop husbandry in general, and moving toward the Asian "Sawah" model of bunded, well-leveled, and puddled rice fields that reduce risk and allow for investment in mineral fertilizer. For example, Becker and Johnson (2001) point out that the construction of field bunds has the potential to significantly increase rice production in West Africa, while also possibly reducing labor requirements for hand weeding and allowing for a more efficient use of mineral N fertilizers.

A similar point is illustrated in Table 4, which shows rice yields, land conditions, and farming practices of two major rice-producing regions in Tanzania in 2009. The importance of irrigation for high productivity is obvious from the table. Under irrigated conditions, farmers achieve yield close to 4 t/ha by applying 37–43 kg of chemical fertilizer per hectare on average and most of the plots are leveled.[18] Moreover, the point we would like to stress is that, even under rainfed conditions, we observe moderately high yield around 3 t/ha when plots have bunds. Many of these plots are also leveled and receive significant amounts of chemical fertilizer.

It is important to mention that markets for inputs and outputs have started to develop in Africa. Kijima et al (2008) reported that, in Uganda, where NERICA varieties were adopted, access to rice millers was greatly improved owing to the rapid increase in the number of rice millers, and rice seeds have been increasingly available from seed suppliers and purchase from neighboring farmers.Tsuboi (2008) reported that the total number of private rice mills in Uganda rose from 183 in 2000 to 591 in 2007. These are good examples to show that markets could respond favorably to the diffusion of new profitable technologies in Africa.

Overall, the Green Revolution in rice in Africa is not an impossible dream at all and, in some places, approaches and methods that have proved successful in Asia have worked well in Africa. But, Africa is diverse and no single approach will suf-

[18]Given the achievement of attractive yields under irrigated conditions or under rainfed conditions with bund in Mbeya, the adoption rates of modern varieties look too low. Note, however, that, if we include two major improved local varieties, India rangi and Faya (or Fayaduma), which have potential yield of 5 t/ha, Mbeya's adoption rates become 5.7% for rainfed without bund, 29.4% for rainfed with bund, and 51.5% for irrigated.

Table 4. Rough rice yield, land condition, and farming practice in Morogoro and Mbeya regions, Tanzania, in 2009.

Item	Morogoro			Mbeya		
	Rainfed		Irrigated	Rainfed		Irrigated
	Without bund	With bund		Without bund	With bund	
Yield (t/ha)	2.0	3.1	3.9	1.3	2.8	3.8
Share of leveled plots (%)	20.5	47.1	69.8	33.3	70.6	77.1
Share of area under modern variety (%)	13.5	67.2	90.7	0.0	0.0	1.7
Chemical fertilizer use (kg/ha)	12.0	64.3	43.8	10.1	45.6	37.3
Sample size	161	17	43	90	17	96

fice. A blend of African methods and innovations and global lessons from Asia and elsewhere can set the stage for a portfolio of successful approaches.

Expectations for the future

Looking forward, it is important for policy and for research to consider whether rice has a special role in African agriculture. Certainly, if past trends hold, it will play an increasingly important role in the African diet, as urbanization and household time constraints favor further increases in consumption. In recent years, imports, made affordable by a low world price, have supported increases in rice consumption in Africa. However, the prospects of higher global commodity prices and the production potential of modern varieties both support the notion that future market conditions will favor African producers as well.

At the start, it is important to recognize that great potential exists for improving productivity outcomes for Africa's rice producers with existing technologies, especially for lowland rice. To a large degree, this potential can be achieved by adopting basic production practices such as the construction of bunds, leveling, flooding, and straight row planting—practices currently used by Asian rice farmers without exception and increasingly by many African farmers as well. As in Asia, most African producers are smallholders, who stand to benefit from increases in local demand and the technological promises of lowland rice. Even so, the consequences of an African Green Revolution in rice will likely differ from Asia's. For one, African diets and African agriculture are more diverse. As a consequence, the gains from increases in rice productivity will not be, by themselves, transformational for the continent. Still, there are places, especially in West Africa, where rice production and consumption figure prominently. Consequently, potential is great for local green revolutions in rice that are suggestive of the broad revolutions that swept through South and Southeast Asia. Moreover, existing trends in urbanization will give rice a greater place in African diets and the potential for productivity-associated welfare gains will grow as well.

In past decades, an important factor that distinguished Africa from Asia is Africa's relative abundance of land. This has not been true of all places; however, for the most part, the availability of land and water resources in Africa to date has differed significantly from what prevailed in Asia in the later decades of the 20th century when Asia's Green Revolution began, and this has had implications for technology choice (Spencer and Byerlee 1976). Consequently, in Asia, finding ways to boost the productivity of limited land resources was a necessary step to improving productivity growth overall. In Africa, the constraints faced by households are more complex and gains in yields alone need not be the chief concern in all places. As a consequence, it is important to have a comprehensive view of productivity that incorporates all input factors and also addresses potential losses stemming from biotic and abiotic risks. At the same time, Africa's land and water resources are not unlimited and there are more binding limits on suitable areas for expanding rice production outside of Africa, even as global demand grows. Taken together, this suggests that land-saving technologies will be more relevant in Africa's future.

In Asia, productivity gains from new technologies feed directly into existing markets for rice—in part because of the proximity of production and consumption centers. In some parts of Africa, rice in general, and especially upland rice in particular, is produced for home consumption, so surpluses generated by higher-yielding varieties do not necessarily have immediate markets. Markets, supported by local traders and processors, may arise endogenously, but with delay. Looking forward, demographic trends point to greater population densities, and the current expansion of transport and communication infrastructure in Africa will work to mitigate these obstacles, but continued support through public investments and supportive policies are key.

For these many reasons, the future role for rice in Africa is more complex and nuanced than it was in Asia, where the Green Revolution in rice began. That does not diminish from the significant role for rice currently in Africa nor should it take away from efforts to develop new technologies that promote productivity gains. Rather, it suggests that the constraints households face in Africa differ from place to place and are less homogeneous than in Asia's past. Consequently, the characteristics of the rice varieties that are key to Africa's success are not necessarily the same as Asia's or even across all of Africa. Certainly, yields and land productivity are important, but so are the consequences of new seed varieties for labor, fertilizer demand, and weather vulnerability. This should shape future research and also guide investments in infrastructure, irrigation, education, and the institutions that back markets. Nonetheless, it must be emphasized that an untapped potential remains for African rice farmers to become more productive now by taking advantage of farming methods now common in Asia. As outlined in this chapter, some of these technologies have been taken up with great success in some areas in sub-Saharan Africa. This, together with lessons from Africa's own successes and the potential associated with new innovations, suggests that a new Green Revolution is possible.

The importance of Africa's success holds not only for Africans. Just as the benefits of Asia's Green Revolution flowed to consumers worldwide, it is hard to imagine a sustained period of affordable food extending far into the future without Africa's participation.

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Notes

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Long-run dynamics of rice consumption, 1960-2050

C. Peter Timmer, Steven Block, and David Dawe

Introduction

"Predictions are hard, especially about the future." Yogi Berra's famous observation is especially true for future rice consumption. We must offer many caveats about the consumption projections put forward in this chapter, especially for the distant projections to 2030 and 2050. Aggregation bias plagues any effort to offer a global projection, the margins of error widen as the time horizon lengthens, and the functional forms used for the econometric estimations may not be appropriate when extended well beyond the time period of data observations. Still, momentous changes are underway in rice consumption, especially in Asia. This chapter brings to bear new data, extensive econometric analysis, and a historical perspective to try to understand the underlying dynamics of these changes.

Global rice consumption does not change much from year to year. Even when rice production falls because of drought, pests, or diseases, enough rice is usually available from storage to keep consumption levels reasonably stable. As Figure 1 shows, rice consumption from 1960 to 2009 rose at a steadier rate than rice production, although the two trend lines are nearly identical because, in the long run, rice cannot be consumed unless it is produced.

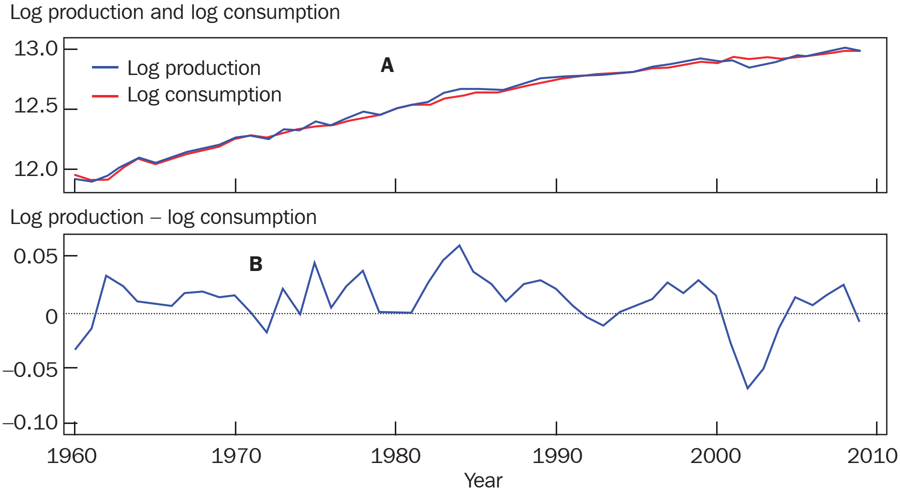

Fig. 1. Global production and consumption of rice, 1960-2009, (A) world totals and (B) percent difference.

If rice consumption is so stable, why try to understand the factors that influence it? Why not draw a simple trend line through the data and extrapolate that as far into the future as necessary for making investment decisions about rice research, irrigation, infrastructure, and marketing facilities? Investments that keep rice production rising smoothly at the rate of projected rice consumption are the surest way to provide food security in the future to the world's poor.

There are two reasons to understand the long-run dynamics of rice consumption. In market-driven economies, consumer demand provides signals to producers about what they should grow, market, and deliver to the retail sector. Market economies are demand-driven economies. We need to understand as best we can what consumers want so we can produce it as efficiently as possible.

The second reason is simple. Underlying the smooth trend of rice consumption are four key factors whose relative contributions to future demand growth are likely to change compared with past experience. Without an understanding of how these forces influenced rice consumption in the past and how that influence will change in the future, it will be impossible to provide useful projections of rice consumption. A straight-line time-series extrapolation is likely to be wide of the mark.

The four basic forces are (1) population growth, (2) income growth (and its distribution), (3) declining real prices for rice, and (4) the gradual shift of workers from rural to urban employment that accompanies a successful structural transformation (Timmer, this volume).

A step-wise regression showing the impact of these four factors is shown in Table 1. Not surprisingly, there is significant multicollinearity among the four independent variables, but the overall explanatory power of the regressions is very high.[1]

Several other forces that have been minor in the past may also play a larger role in the future: an increasing share of rice consumption in Africa, where it is growing rapidly, may gradually erode the overwhelming dominance of rice consumption in Asia, where it is growing much more slowly, if at all; changing age structures may drive different dietary preferences, with rice losing out to wheat products, animal protein, and fruits and vegetables; and tastes may change in a globalized economy, even holding constant all the other factors that influence rice consumption (Huang and Bouis 1996).

Finally, a large unknown for the more distant projections will be the impact of climate change on dietary patterns via differential impact on the costs of production of rice, wheat, and maize. Current climate models, for example, suggest that wheat production will be much more strongly affected in the Indian subcontinent than rice. If so, rice would become relatively cheaper, and thus a more attractive purchase for the poor (Nelson et al 2009).

Huge uncertainties surround the changing impact of all these factors. This chapter seeks to understand how they have influenced rice consumption in the past in

[1]In Table 1, the variable "year" is used instead of "agricultural population share" because the two are almost perfectly collinear and it seemed inappropriate to attribute all trend effects to agricultural population share. A fuller specification using per capita rice consumption as the dependent variable is shown in Table 2.

Table 1. Determinants of global rice consumption, 1960-2009.[a]

Item	(1)	(2)	(3)	(4)
Log global GDP	3.77**	8.35***	8.70***	8.21**
	(2.13)	(10.25)	(10.10)	(2.29)
Log (global GDP)^2	–0.05*	–0.14***	–0.15***	–0.14**
	(1.75)	(10.98)	(10.79)	(2.32)
Log population total		1.93***	1.85***	1.92***
		(12.38)	(10.66)	(3.51)
Log export price$_{(t-1)}$			–0.011	–0.011
			(1.30)	(1.30)
Year				–0.002
				(0.14)
Constant	–55.15**	–140.19***	–144.63***	–135.25*
	(2.04)	(11.54)	(11.36)	(2.01)
Observations	49	48	48	48
R^2	0.99	1.00	1.00	1.00

[a]Robust t-statistics in parentheses. * = significant at 10%, ** = significant at 5%, *** = significant at 1%.

order to make the best projections possible of rice consumption in the future. These projections are important because they help governments, donors, and businesses allocate investment resources to increasing rice production. These investments often take a very long time to pay off—consumption projections are needed for at least 20–30 years into the future. The more accurate the rice consumption projections, the better chances decision makers have of making the right investment decisions, and the more likely the world will have enhanced food security for generations to come.

The analytical task is divided into three parts. The first is a brief review of earlier efforts to project rice consumption, including possible biases generated by different methodologies, the nature of data used in the analysis, and even how the research question is specified. This section draws on an early review in the Indonesian context by Timmer (1971), an Asia-specific review by Ito et al (1989), and a recent one in the Indian context by Dutta and Gulati (2009). A fairly robust conclusion from the literature review is that most efforts to project rice consumption (especially in India, where significant analytical effort has been put into the effort) *have significantly overestimated the rate of growth*. It is important to understand the source of this bias.

The second section of the chapter provides the core econometric analysis of long-run rice consumption trends for several important countries and for the global total. The global total is known with some confidence since 1960, so there are 50 observations to use in identifying the impact of the four main factors noted above.[2] This

[2]Annual time-series data on rice consumption for well over a century are available for several countries, including Indonesia (since 1880), Japan, and Thailand. These countries could be the topic of extensive further research.

Table 2. Regressions using the global aggregate data (dependent variable: log global rice consumption per capita).

Item	(1)	(2)	(3)	(4)	(5)
Log GDP per capita[a]	6.12***	7.62***	11.46***	12.07***	11.86***
	(5.40)	(6.88)	(13.75)	(14.75)	(11.91)
Log (GDP per capita)^2	–0.35***	–0.44***	–0.72***	–0.75***	–0.74***
	(5.10)	(6.59)	(13.75)	(14.63)	(11.29)
Log rice price$_{(t-1)}$[b]		–0.035***		–0.008	–0.007
		(3.42)		(0.85)	(0.71)
Year			0.012***	0.012***	0.015*
			(12.00)	(7.37)	(1.75)
Agricultural population share					0.84
					(0.34)
Constant	–22.66***	–28.39***	–66.25***	–67.74***	–72.84***
	(4.82)	(6.25)	(13.55)	(13.15)	(4.41)
Observations	48	48	48	48	48
R^2	0.92	0.93	0.96	0.96	0.96

[a]GDP measured in constant 2000 US$. [b]Rice price is the world export price reported by IRRI.
Robust t-statistics in parentheses. * = significant at 10%, ** = significant at 5%, *** = significant at 1%.

section provides the basic parameters used in making projections of rice consumption, and it contains some surprises. The Asian diet is diversifying very rapidly (Pingali 2004). Great uncertainty remains over the exact implications of these changes for the future of rice consumption, and this section also highlights these uncertainties.

The third section of the chapter draws on a quite different source of data to understand the determinants of rice consumption: the household expenditure surveys conducted by a number of countries, often over extended periods of time. We can use surveys only where access to the quantity of commodity consumption by expenditure (income) group is possible, but even so we have observations for Indonesia for 1963-64, 1967, 1976, 1987, 1999, 2002, and 2006. Multiple observations are also available for India, the Philippines, and Bangladesh, a detailed geographic breakdown is available for China for 2005, and there are single observations for another six countries. We assemble these data in a common format: *quantity* of rice consumed per capita by expenditure/income quintile, and then examine the data for patterns across time and countries. No econometric results are presented using these data, as the original household files are not available. Still, the data themselves, and the numbers that summarize them, are quite striking and help inform the projections of rice consumption in the future.

The final section of the chapter provides our best "benchmark" projections of rice consumption for 2020, 2025, 2030, and 2050 (using our 2010 estimates as the base). The primary goal is to develop transparent and clearly justified projections for the global total of rice consumption. We use three models to do this: first, a simple "baseline" projection is built on a regression model incorporating the four main drivers of changes in rice consumption noted above—income, population, price, and the global trend of share of the rural population in the total (which is almost perfectly collinear with time), with the estimated coefficients applied going forward at rates of change that are relatively conservative—income per capita growth of just 1.5% per year and rural-to-urban migration at its historical trend rate. As expected, even this simple structural model is bedeviled by strong multicollinearity among the four independent variables, but, also as expected, the overall fit is extremely good and key insights emerge into what drives rice consumption. The advantage of this baseline model is its simplicity and transparency—the time-relevant trends are all reflected in the projections.

Second, we use this structural model of global rice consumption, estimated using the four independent variables as well as a time trend, to project rice consumption on the assumption that per capita economic growth is 2.0% per year—close to the historic average of 1.9% per year from 1961 to 2010, and that the accompanying structural transformation is also somewhat faster. Because our model is quite sensitive to rates of growth in per capita incomes, the projections from this "structural" model are quite different from those in the "baseline" model.

To cope with the problems of multicollinearity and aggregation bias, our third model introduces exogenous parameters that are based on more detailed country analysis and on insights from the cross-section consumption analysis. Aggregation of consumption totals from individual countries (or even regions or households) into a global total can hide a rapidly growing but small component of consumption, as in Africa. Of course, aggregation bias can work in the other direction by masking the impact of recent and rapid declines in larger components, such as Indonesia or China. Aggregation does not necessarily impose a bias on projections up or down; it just hides the details of differing consumption paths. Similarly, multicollinearity does not impose a bias on coefficients or projections from them; it just reduces the statistical significance of individual coefficients and hence our confidence in exactly what is driving the projections. Still, much can be gained in our structural understanding of changes in rice consumption by using more detailed, disaggregated data, and analysis of these data yields our "best judgment" projection model. This model requires that considerable judgment be incorporated into the final projections because a number of parameters are inserted exogenously, based on analysis of the disaggregated data. Good judgment is obviously in the eye of the beholder. We try to be open about what judgments we make and why, and how they affect the long-run projections.

We also offer highly preliminary judgments on where rice consumption will take place, both by continent and by rural-urban location. Greater reliance on consumption at some distance from production implies, of course, greater investments in the transportation and marketing infrastructure needed to move rice from farm to table. The diverse impact geographically of climate change also suggests that greater trade will be needed to ensure that global supplies are available locally where they are needed. A highly speculative discussion of the potential for climate change to alter our basic rice consumption projections concludes the chapter.

Projecting rice consumption: a review of the methodological issues

No single methodology is suitable for projecting rice consumption. Even projections for world rice consumption for 2030 can vary widely—from a low of 380 million tons to a high of 540 million tons in a recent review by Abdullah et al (2005). That range is far too wide to be useful. Some methodological choices need to be made, and defended, that will generate a more plausible range of consumption projections.

This is an old problem. It has long been recognized that the two basic sources of information on food consumption—aggregate time series and household-specific cross-section data—offer quite different insights into what drives consumer behavior. A very early example illustrates the problem: cross-section analysis of consumption of processed tomatoes in the United States showed a negative income elasticity for the most common products—canned peeled tomatoes and tomato purée—and yet the time-series consumption data showed a smooth increase in the total volume of processed tomatoes. The puzzle was explained by the changing structure of demand for these products, as canned tomato juice was a rapidly rising share of the total and its consumption was strongly responsive to income growth (think Bloody Marys) (Timmer 1963). We will see the same aggregation puzzle arise with respect to the consumption of rice in Africa and its role in the global total.

Much of the early literature on consumption projections stems from the problems facing economic development planners: how could industrial investments be targeted to best meet future consumption needs? With only little or no time-series data available for newly independent countries, the recourse was to cross-section data and parameters as a substitute (Pearce 1964, Houthakker and Taylor 1966, Timmer 1971, Thomas 1972, Powell 1974, Phlips 1974). Even relatively small samples of households yielded substantial information on different consumption patterns by income, place of residence, education level, and demographic composition. Because economic planners were not interested in how relative or absolute prices would vary over time, the lack of variance in commodity prices in most cross-section data was not a problem.

What *was* a problem was the growing realization that different households might have different consumption patterns for reasons other than those observed in the data. The problem of "unobserved variables" was first recognized in the production function literature, especially because cross-section differences in household/firm productivity seemed to be subject to "management bias," which biased the estimated coefficients for measured inputs that might be correlated with good management, such as capital or fertilizer (Griliches 1957, Mundlak 1961, Hoch 1962, Massell 1967). The solution was to use panel data, with observations on individual households over time, so that the "fixed effects" associated with unique and unchanging characteristics of households or firms could be isolated from the impact of variables that changed over time. Panel estimation is now the standard for estimating parameters when pooled cross-section and time-series data are available.

For the analysis here, we can make only limited use of this approach, to control for country-specific effects when we have a panel of country data for a number of years. Although countries clearly have definable consumption preferences that are not necessarily related in the short run to observable variables such as incomes, structure of the economy, or relative prices, great heterogeneity also exists within countries across households. To understand the impact of this heterogeneity, we will need to use the richness of cross-section data, despite all the "static-ness" of such data.

Indeed, when we have a time series of cross-section data, even if only for quintiles rather than individual households, we can treat the data as a "pseudo panel" on the assumption that each quintile represents thousands of individual households. The hope is that the characteristics of being "poor" (in the bottom quintile, for example) outweigh any changing characteristics that come about because of the entry and exit over time of individual households from this category, and quintile. Unfortunately, not much evidence is available on the extent of "poverty churning," and what there is suggests that entry and exit from poverty are quite substantial (McCulloch et al 2007). Still, analysis of the "time series" of quintile-level rice consumption in Indonesia, India, and Bangladesh is quite revealing.

By judiciously combining time-series and cross-section analysis, we hope to avoid the biases that come from sole reliance on either type of data. In a review of recent studies that made projections of food commodity demand and supply in India, Dutta and Gulati (2009) discovered a *systematic upward bias*, especially in the demand projections. They are still in the process of understanding the exact source of this bias, but they are inclined to think that it is at least partly methodological and partly data-based.

Dutta and Gulati conclude as follows:

> "The above analysis discusses the projection techniques, the assumptions made by various studies in demand and supply estimations for 2010, 2020, and 2026. The results indicate a lot of variability despite most of the studies using the NSS data for demand estimations. This paper also conducts a validation exercise on the estimates for foodgrains demand and supply for 2000 by several studies. One crucial observation in this regard was the overestimations by almost all the studies both on the demand and the supply side. The demand overestimations were higher than the supply side. This was more so using NSS data as compared to using NAS data. All of this has raised doubts on the reliability of the model to be used for making such demand/supply estimations for the future. To tackle the food security issue of a nation, it is important for the policymakers to suggest appropriate remedy measures, which heavily depends on what the future demand and supply scenario of the country will be. Our aim is to develop such a robust model for future demand and supply estimations. Since the demand side is heavily overestimated by various studies, a lot of accuracy is needed while reporting the demand-side results." (Dutta and Gulati 2009, p 49.)

The key point of this careful survey of food demand modeling in India is that the historical projections based on these models have had a significant upward bias. The standard models have clearly missed an interior dynamic that is driving growth in rice consumption at slower rates than the estimated parameters would indicate. Declining income elasticities of demand for rice, perhaps driven by more rapid rural-to-urban migration than was apparent in the historical time series, would account for this pattern.

Time-series analysis of trends in rice consumption, 1960-2009

Rice consumption in the world

This section provides a broad overview of the characteristics of rice consumption at the global level. Although different countries have distinctly different dynamics with respect to rice consumption (indeed, provinces, states, and districts also vary widely, as do individual households), it is useful to start the analysis with the global aggregate. This aggregate has its own complicated dynamics and will be a useful test of our methodology.

Our point of departure is Figure 2, which illustrates the trend in global rice consumption per capita from 1961 to 2008. Global rice consumption per capita has increased consistently (at least until the early 2000s) since 1960. The average growth rate of per capita consumption over the entire period 1961-2008 was 0.56% per year. Yet, casual inspection of Figure 2 suggests that the growth rate of rice consumption per capita changed in the early 1990s. Indeed, for the period 1961-89, the growth rate

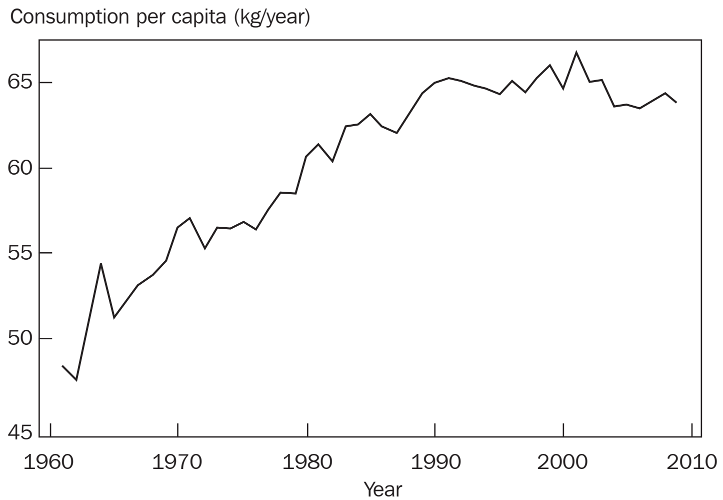

Fig. 2. Trend in global rice consumption per capita, 1961-2008.

of global per capita rice consumption was 0.9% per year; for the period 1990-2008, that rate fell to –0.11% per year. This change raises central questions for this chapter:

(1) What determinants of global rice consumption can explain this shift?

(2) What does this shift imply for projections of future global rice consumption?

In exploring the determinants of global rice consumption per capita, we turn first to the income elasticity of demand and estimation of a global Engel curve for rice. Figure 3 provides a first cut at estimating the global Engel curve for rice consumption per capita—it illustrates the relationship between log rice consumption per capita and log income per capita in the world, with year markers for the individual data points. This nonparametric Engel function suggests that rice was a normal good at the global level until the mid-1990s, and had become a mildly inferior good thereafter. The portion of this Engel function that depicts the years 1961-95 is essentially linear, and a linear regression for these years indicates that the global income elasticity of demand for rice was 0.23 ($P = 0.000$); post-1995, the linear estimate for the income elasticity of demand is –0.08 ($P = 0.032$). Figure 3 thus suggests the possibility that global rice consumption per capita began to decline in the mid-1990s because global income per capita had reached a level at which rice became an inferior good, in the aggregate. This turning point in Figure 3 occurred at a time when global income per capita had reached approximately $4,700 (in constant 2000 US$).

Figure 3 considers only the two-dimensional relationship between consumption and income. Obtaining a clearer picture of the income elasticity of demand for rice requires additional control variables. Table 2 presents regression results for rice consumption in which we specify a quadratic term for income, and control as well for lagged rice price in world markets, agricultural population share, and a time trend. Our results strongly reject the hypothesis that the Engel curve for rice is log-linear in

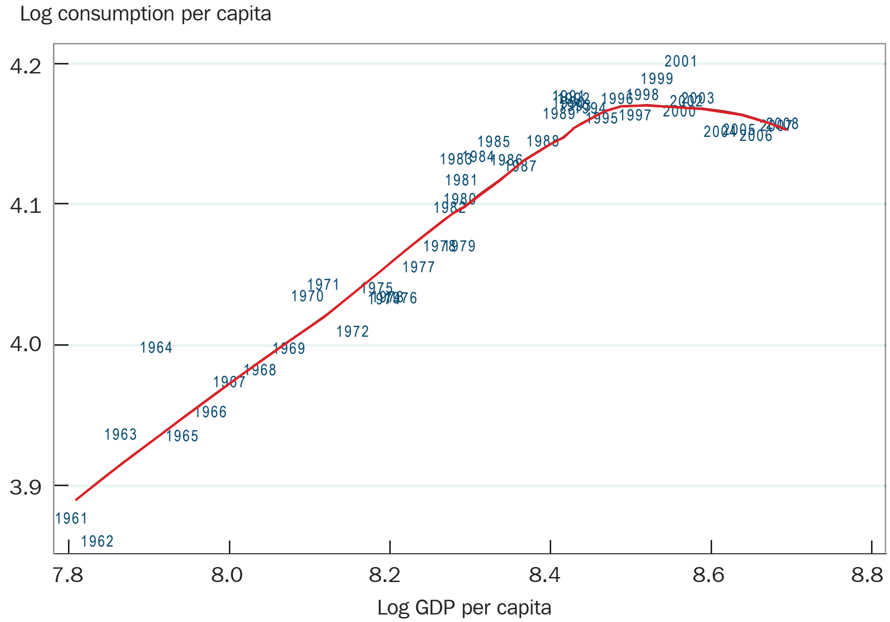

Fig. 3. Nonparametric Engel curve for rice consumption per capita, 1961-2008.

income. The quadratic specification fits the data well (as do other specifications, such as the log-log inverse function and a cubic function, although the quadratic function is always the best and most parsimonious fit).

It is possible in principle to estimate the price elasticity of demand for rice by including the world rice price in the regressions reported in Table 2. However, at the global level, we cannot assume that the price of rice is exogenous. Thus, we introduce the lagged price of rice to control for endogeneity (in column 2). The coefficient is highly significant, with an estimated price elasticity of –0.035. Global demand for rice is very inelastic with respect to the world rice price (lagged one year), but, of course, most countries do not permit their consumers to face this price directly, and any serious effort to understand consumer response to changes in rice prices would need to be done at the country level.

In column 3, we introduce a time trend, which knocks out the significance of the price term while demonstrating an "exogenous" increase in world rice consumption of 1.2% per year, holding incomes and prices constant. Finally, we test the impact of rural to urban migration by including the share of the work force in agriculture (agpopshr). Then, none of the three time-related variables remain significant. Of course, agricultural population share and world rice prices are highly correlated with time.[3]

[3] The correlation of time with the world export price of rice is –0.72, while time and agricultural population share are almost perfectly (negatively) correlated. Figure 5 shows the high correlation of these two variables over time. Only cross-section data, with much greater variance by country and over time in the share of the work force in agriculture, can reveal the impact on rice consumption of workers moving from rural to urban areas. See the next section for further discussion and analysis.

The results reported in the final column of Table 2 suggest that rice becomes an inferior good at the global level when income per capita exceeds \$3,154 in constant 2000 US\$ (or when log income per capita exceeds 8.06). The same specification suggests that the estimated income elasticity of demand at the 10th percentile of income per capita (\$2,826) is 0.157, which is not statistically different from zero (P = 0.179); at the sample median income per capita (\$4,125), the income elasticity is –0.400 (P = 0.007); and, at the 90th percentile of sample income per capita (\$5,527), the estimated income elasticity of demand is –0.829 (P = 0.000). Similar results are obtained using other functional specifications, but it is also useful to examine what happens to the Engel elasticity for rice *without* restricting the functional form.

Thus, our final step in estimating the global Engel curve for rice is to relax the assumption that the Engel curve is quadratic in income while still controlling for world rice price and a time trend. To implement this, we estimate a semi-parametric regression of the form

$$y_i = X_i\,\beta + g(Z) + \varepsilon_i \qquad (1)$$

where X includes a vector of control variables (that enter linearly) and g(.) is an unknown function relating the dependent variable to the key independent variable (Z) in a given model. Figure 4 presents the resulting Engel curve for rice. This semi-parametric Engel curve is roughly quadratic, but departs from a purely quadratic form with an interesting asymmetry: the unconstrained Engel curve rises gradually from lower levels of income toward its maximum and then declines rapidly.

We capture the income elasticity of demand at each point along this Engel curve (e.g., the slope of the function) in the bottom panel of Figure 4. As implied by the slope of the Engel curve in the top panel of Figure 4, *the income elasticity of demand for rice at the global level declines at a slightly accelerating rate* throughout the range of income per capita, and rice becomes an inferior good when income per capita exceeds approximately \$3,570 (constant 2000 US\$). Our "best judgment" projections use insights from this nonparametric specification of the Engel elasticity rather than simple extrapolation from the quadratic specifications.

Asian subsample

A specific focus on Asia is justified by the fact that more than 88% of global rice consumption in 2010 is in Asia. Our full Asian sample includes Bangladesh, Cambodia, China, India, Indonesia, Japan, Republic of Korea, Lao PDR, Malaysia, Nepal, Pakistan, the Philippines, Sri Lanka, Thailand, and Vietnam. In some specifications, we eliminate Pakistan (primarily a wheat-consuming country), along with Cambodia, Lao PDR, and Nepal (for reasons of data quality). Table 3 repeats the Engel curve specification explored in Table 2, with this Asian subsample.

The aggregate Asian Engel curves estimated in Table 3 retain the quadratic form of the global sample. In the full Asian subsample, the income elasticity of demand at the 10th percentile of income per capita (\$211) is 0.28 (P = 0.000); at the sample median income (\$710), the income elasticity is 0.138 (P = 0.000); and, at the 90th percentile of income per capita (\$10,546), the estimated income elasticity of –0.173 (P = 0.000) indicates that rice is an inferior good. Based on the specification in column

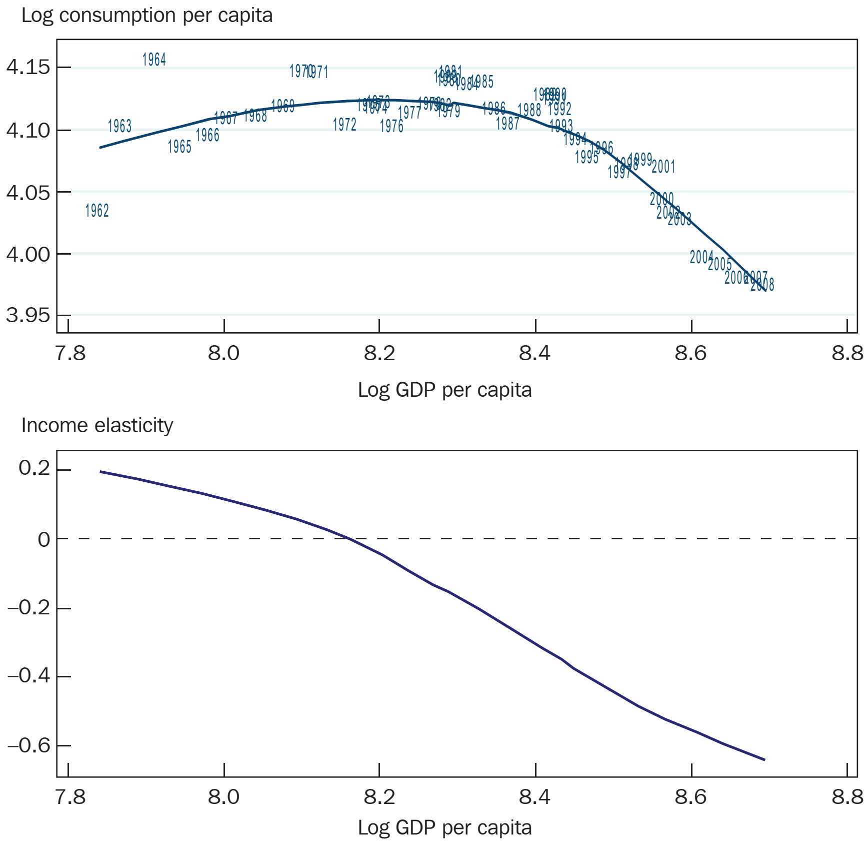

Fig. 4. Semi-parametric Engel curve for rice, with income elasticities.

3, which includes lagged world price and agricultural population share, rice becomes inferior when income per capita reaches $2,364, versus $3,570 for the global sample. The Engel elasticities for rice in the Asian subsample seem to be less negative than in the global sample, but that is simply because Asian per capita incomes are lower. As noted, rice becomes an inferior good in Asia at income levels much below the turning point in the global sample.

The price elasticity of demand estimates presented in Table 3 provide suggestive evidence of quite inelastic demand, with estimates of –0.11 for the full sample. These estimates are not statistically significant when we cluster the standard error at the country level (to account for a possible lack of independence of observations within countries); yet, without clustering, these point estimates are statistically different from zero at conventional levels.

Country-specific estimates of Engel curves reveal that not every country presents a typical quadratic Engel curve. Income elasticities of demand calculated at each country's median income level over the sample period are available from the authors.

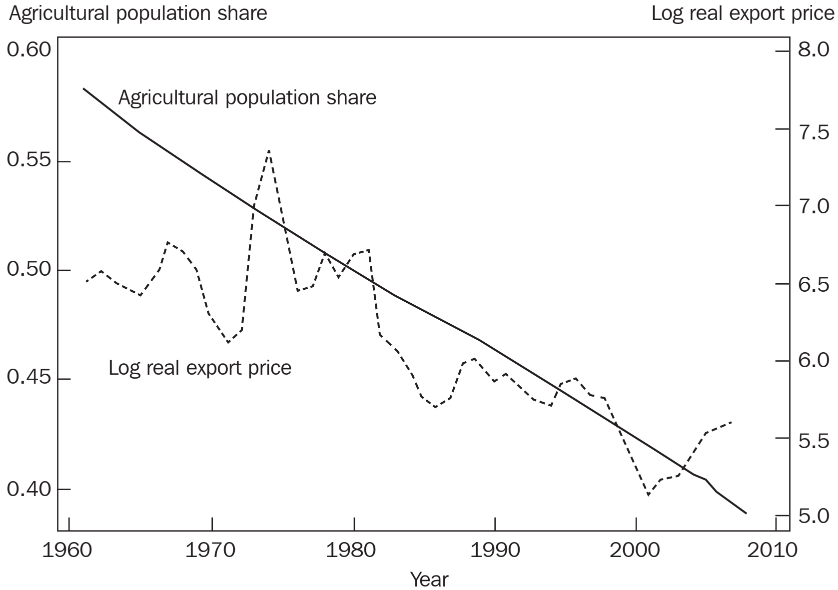

Fig. 5. Agricultural population share and log real export price of rice over time.

We observe substantial heterogeneity across countries, along with heterogeneity in the income level at which rice becomes inferior in each country for which an estimate is possible.

Figure 6 presents country-specific semi-parametric Engel curves for the individual Asian countries and the full Asian sample, controlling for agricultural population share. This disaggregation reveals substantial heterogeneity within the Asian sample. At any given level of income per capita, variation is substantial in per capita consumption (that is, the Engel curves are of varying height relative to one another). The wide range of horizontal locations and lengths of these curves indicates substantial heterogeneity in both income levels and growth rates over the sample period (1960-2007). The aggregate Engel curve thus emerges as a smooth picture, yet one that aggregates widely varying country experiences.

Finally, we make a crude effort to disaggregate rice consumption into the major consuming regions. Figure 7 shows the time trends for Asia and the Middle East, North and South America, and Africa. These regions, plus the "rest of the world," are then the subject of a standard time-series analysis using time and time squared as the independent variables.[4] The results are shown in Table 4. These regressions are used as the basis for the regional projections in the section "Projections of rice consumption," which are presented to show the potential trade implications of varying growth rates of rice consumption in different regions. It is noteworthy that the quadratic term

[4]Note that the data used for "Asia & Middle East" in Figure 7 include all countries in those regions, as compared with the Asian subsample described above.

Table 3. Pooled regressions for Asian subsample (dependent variable: log rice consumption per capita).[a]

Item	(1)	(2)	(3)	(4)
Log GDP per capita	0.505***	0.457***	0.879***	1.516***
	(0.090)	(0.083)	(0.093)	(0.140)
Log (GDP per capita)^2	–0.036***	–0.033***	–0.048***	–0.089***
	(0.006)	(0.005)	(0.006)	(0.008)
log world rice price$_{(t-1)}$		–0.066	–0.110***	–0.084**
		(0.040)	(0.039)	(0.040)
Agricultural population share			0.019***	–0.037***
			(0.002)	(0.006)
(Agricultural population share)^2				0.0005***
				(0.000)
Constant	2.908***	3.511***	0.371	–0.656
	(0.324)	(0.385)	(0.509)	(0.610)
Observations	598	598	598	598
R^2	0.03	0.03	0.10	0.16
Income elasticity at sample median income	0.061*** (0.019)	0.048*** (0.018)	0.291*** (0.033)	0.416*** (0.046)

[a]Robust standard errors in parentheses. * = significant at 10%, ** = significant at 5%, *** = significant at 1%. For the 4th column, the slope for agricultural population share at the sample mean of 69.3 is 0.029 (standard error = 0.003).

for the African growth regressions is not significant and thus total rice consumption in Africa grows at a steady 3.8% per year. Because all other regions show a declining growth rate for rice consumption, Africa's steady growth makes it a large factor in global rice demand as early as 2030.

Rice consumption by income class, selected countries

By their very nature, aggregate time-series data conceal the possibly wide heterogeneity of rice consumption among individual households. This section demonstrates that the heterogeneity is indeed very wide in most of the countries for which disaggregated data are available. The heterogeneity is driven by household incomes, by whether the household lives in urban or rural areas, and by many other factors, including tastes.

For this chapter, we have developed a unique set of data—rice consumption by income (or expenditure) quintile, usually for rural and urban households separately, often for several time periods, for a total of 11 countries. China, India, and Indonesia

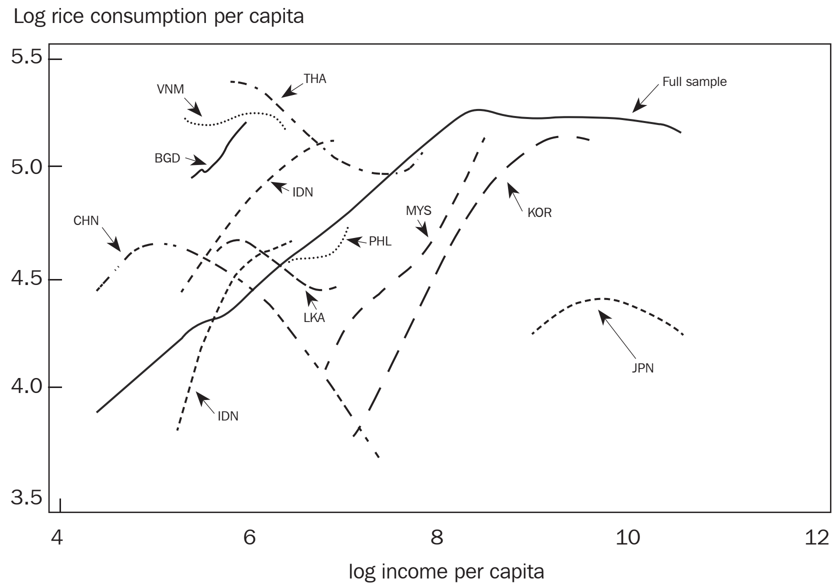

Fig. 6. Country-specific semi-parametric Engel curves, 1960-2007, controlling for agricultural population share.

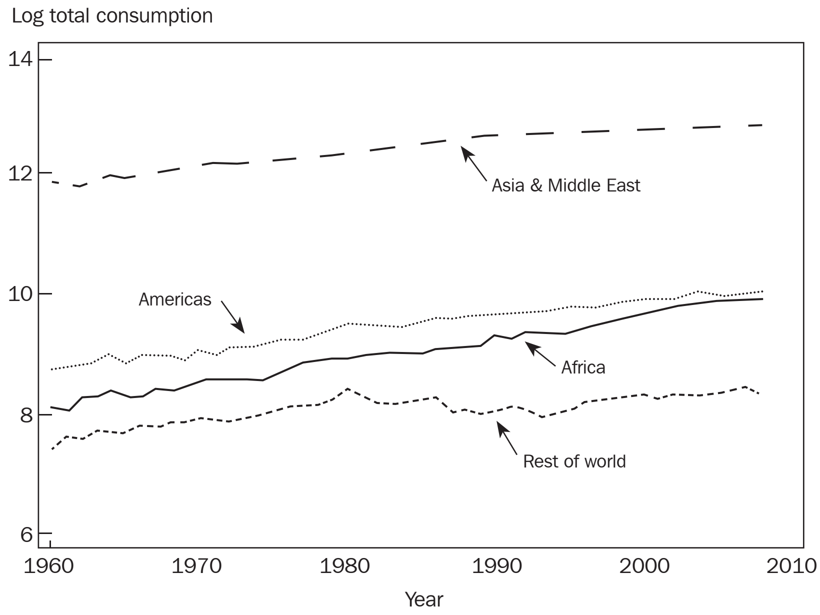

Fig. 7. Rice consumption trends by region.

alone account for 60% of world rice consumption, so having disaggregated data for these countries is crucial to understanding the underlying dynamics of rice consumption. The Philippines and Vietnam are also large rice consumers—the Philippines is the world's largest importer and Vietnam is the second largest exporter. Bangladesh is a major rice producer and consumer, with 70% of its daily caloric intake coming from rice. Some geographical diversity is also reflected with data from Cambodia, Nepal, Madagascar, Panama, and Nicaragua. In total, more than three-fourths of global rice consumption is accounted for by the countries for which data disaggregated by income quintile are available (these data are available from the authors) and for which the analysis is reported in this section.

Six patterns stand out from these data. First, there is overwhelming diversity of rice consumption levels across countries and regions within a country. Just in China in 2005, for example, rice consumption in rural Shandong—China's second most populous province with 94 million inhabitants—averages less than 0.07 kg per capita per week, whereas, in rural Jiangxi Province, with 44 million inhabitants, rice consumption averages over 4.3 kg per capita per week.

Second, there can be sharp differences in rice consumption by income class for a given country or region at one point in time, especially if it is quite poor. In rural Java-Madura in 1963-64, rice consumption by the top income quintile was 2.55 kg per capita per week, more than three times the level of the bottom quintile. At that time, of course, rural Java was desperately poor. The ratio for rural India in 1983 was 2.2, and 1.7 for rural Anhui Province in China in 2005.

Third, large differences between rural and urban rice consumption are common, but the differences change substantially over time and by income classes. For example, in 1963-64 Java-Madura, rural rice consumption in the bottom income quintile was only about half that of the same urban quintile, but in the top income quintile rural rice consumption was slightly higher (Fig. 8). In 2004-05 India, rural rice consumption in the top quintile was about half again as large as in the top urban quintile. The rural-urban differences are especially sharp in China in 2005. In Jiangxi Province, rural rice consumption is more than 3.3 times higher than urban rice consumption when averaged across income quintiles and it is 3.7 times higher in the top income quintile. In most important rice-consuming areas, rural rice consumption is significantly higher than urban rice consumption. These patterns have sharp implications for future levels of rice consumption when a larger share of the population works in urban areas.

Fourth, the income elasticity of demand for rice from these cross-section data depends on whether the household lives in a rural or urban area. Most income elasticities for urban households are now zero or negative (for example, see the rotation of Engel curves that has taken place over time in urban Indonesia in Fig. 9). Only Madagascar in 1993 is an exception. Excluding Madagascar (and China), per capita consumption quantity for the top urban quintile is on average 9% lower than in the second urban quintile (this calculation uses only the most recent data for India and Indonesia). For urban China in general, the rule holds, but several poorer provinces still show a positive response of rice consumption to higher incomes in urban ar-

Table 4. Quadratic growth specification for total rice consumption by region (dependent variable: log total rice consumption).[a]

Item	(1) World	(2) Asia & ME	(3) Americas	(4) Africa	(5) Rest of world
Year	1.129***	1.214***	0.756***	0.038***	1.414***
	(16.83)	(16.14)	(4.97)	(60.6)	(3.52)
$(Year)^2$	–0.0003***	–0.0003***	–0.0002***		–0.0004***
	(16.50)	(15.85)	(4.78)		(3.48)
Constant	–1,130***	–1,214***	–768***	–67***	–1,409***
	(16.98)	(16.26)	(5.09)	(60.4)	(3.53)
Observations	49	49	49	49	49
R^2	1.00	0.99	0.99	0.99	0.74

[a]Absolute value of t-statistics in parentheses. *** = significant at 1%.
Source: Data from United States Department of Agriculture.

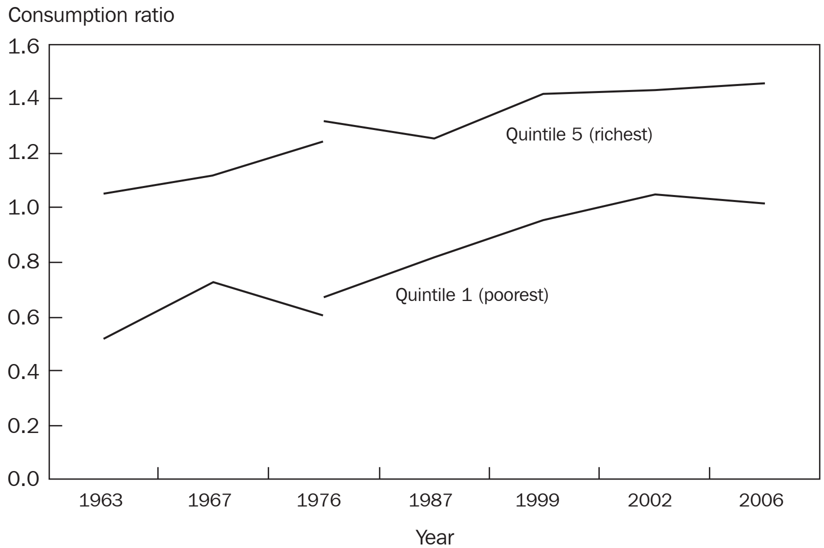

Fig. 8. Ratio of rice consumption in rural areas to rice consumption in urban areas for top and bottom quintiles, Indonesia. There are two data points for 1976, one for Java and Madura and the other for all Indonesia. Data in the figure for Java and Madura cover 1963-76, while data for all Indonesia cover 1976-2006.

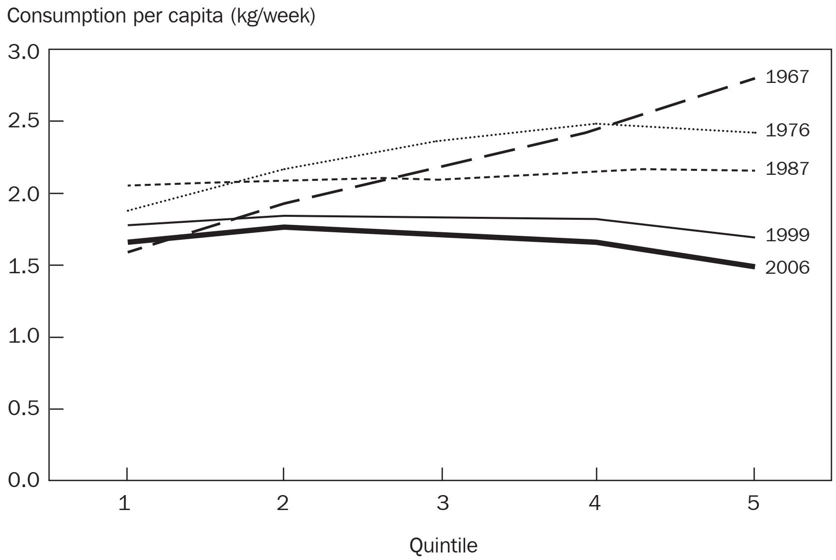

Fig. 9. Engel curves over time for urban Indonesia. Data for 1967 refer to Java and Madura.

eas—Anhui, Henan, Tibet, Shaanxi, and Gansu, for example (these provinces tend to be in traditional wheat-eating areas, see below).

Income elasticities are more positive in rural areas, no doubt because incomes in these locations are lower on average. There is still at least a modest increase in rice consumption across income quintiles in all countries and most provinces of China. Still, even this effect is dropping sharply over time. In Indonesia, for example, the ratio of rural rice consumption in the top income quintile to that of the bottom quintile dropped from 3.29 in 1963-64 (for Java-Madura) to 2.50 in 1976 (all Indonesia) and to just 1.30 in 2006. In India, the same ratio dropped from 2.21 in 1983 to 1.07 in 2004-05 (Fig. 10). Further income growth in rural Asia is likely to lower the response of rice consumption to income levels even further.[5]

Fifth, there is a very dramatic convergence of rice consumption patterns across income classes in those countries where we have multiple observations—Indonesia and India (Figs. 11 and 12). This convergence is partly a result of flattening Engel curves across income classes as overall income levels rise (Fig. 9), but it is also possible that tastes are changing in ways that make food consumption patterns more uniform across households, whatever their income levels and place of residence.

Finally, the argument that tastes are changing to become more homogeneous, especially in urban areas, seems especially relevant in China. In rural areas in China, the latitude of the capital city is a strong determinant of per capita rice consumption. In low latitudes, rice has long been the traditional staple crop, whereas, in high latitudes, wheat is the traditional staple, and rural dwellers still (at least in 2005) stick to traditional consumption patterns. Thus, a one degree decline in latitude increases annual rice consumption per capita in rural areas by 7.3 kg of milled rice (Fig. 13). As shown in Figure 14, rural consumption of rice is directly correlated with production in the same province—a function of latitude, of course. But, in urban areas, this relationship is breaking down—the coefficient in urban areas shows that a one-degree decline in latitude increases annual rice consumption in urban areas by just 1.5 kg of milled rice, and provincial production of rice has relatively little impact on urban consumption. Thus, tastes are becoming more homogeneous in urban China, with traditional rice eaters reducing rice consumption and traditional wheat eaters increasing rice consumption.

Another potentially important trend relates to changing tastes across age cohorts, as younger people who are more exposed to global culture shift out of rice and into wheat, even after controlling for urban or rural location. In Malaysia, the ratio of rice to wheat consumption is much higher for older households in both rural and urban areas (Fig. 15). Ishibashi et al (2005) and Mori et al (2000) both found a similar pattern in Japan, with younger households consuming less rice. Young Asians will not stop eating rice, of course. But, their globalized tastes mean that they will probably eat less rice than their parents, helping to accelerate the trends that occur due to rising incomes and urbanization.

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[5]In Indonesia and India, where data are available to disaggregate the top income quintile into smaller increments, such as deciles or smaller, there is clear evidence of negative income elasticities for rice consumption in the top half of the top income quintile, even in rural areas.

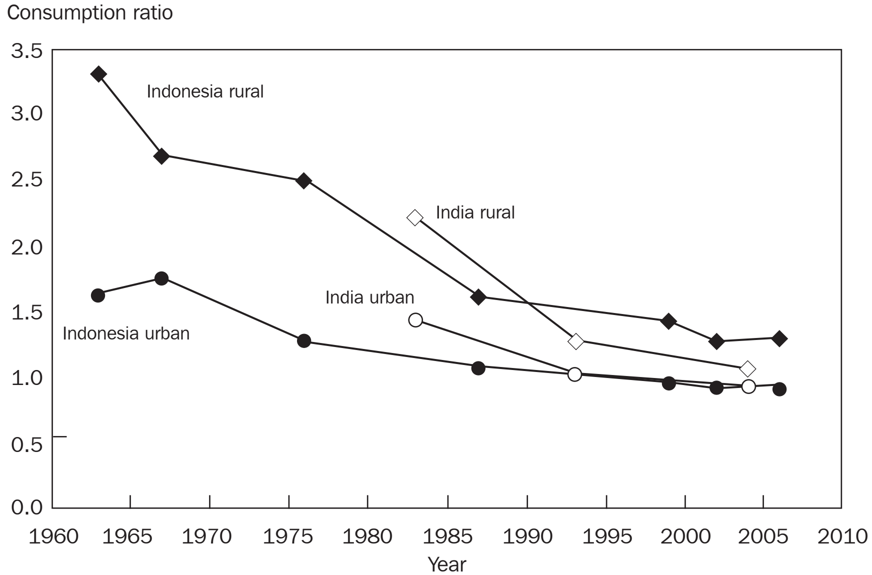

Fig. 10. Ratio of rice consumption in the top quintile to rice consumption in the bottom quintile over time, India and Indonesia, rural and urban areas. Data for 1963 and 1967 for Indonesia refer to Java and Madura only.

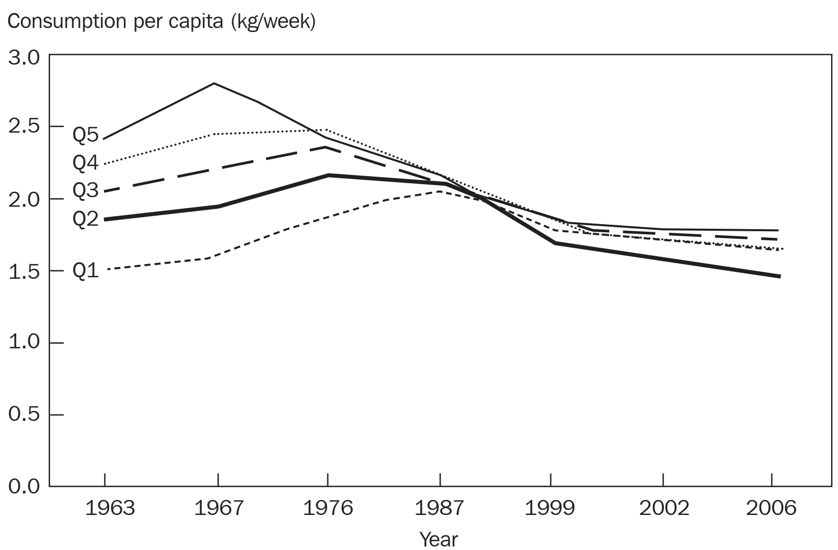

Fig. 11. Per capita rice consumption by quintile (Q) over time, Indonesia, urban areas.

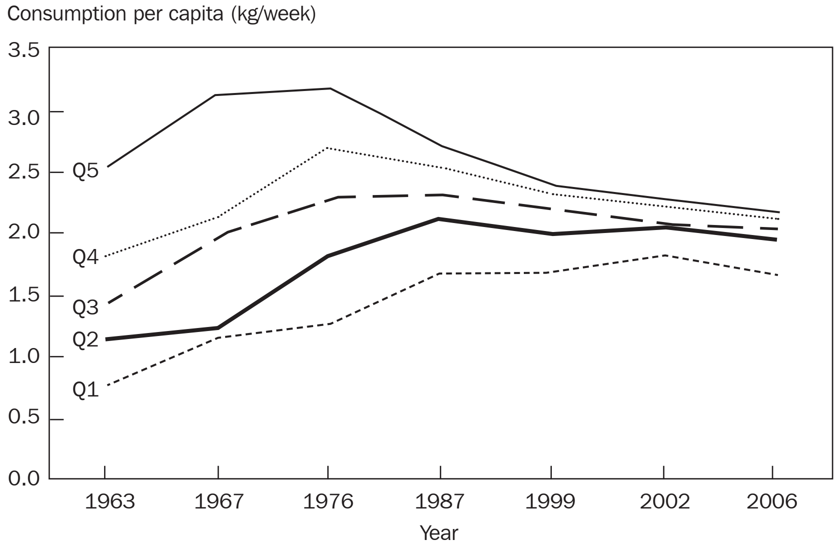

Fig. 12. Per capita rice consumption by quintile (Q) over time, Indonesia, rural areas.

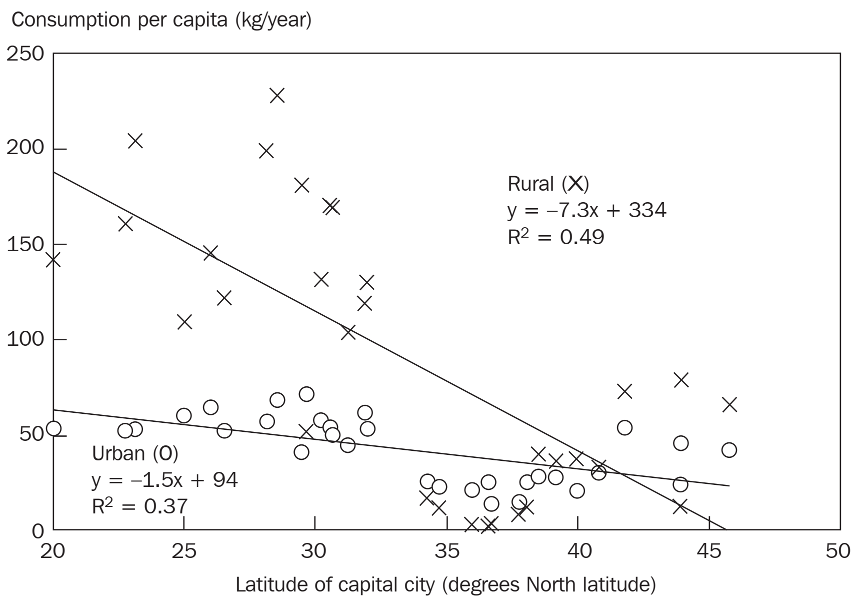

Fig. 13. Annual rice consumption per capita as a function of latitude of the capital city, urban and rural areas, China, 2005.

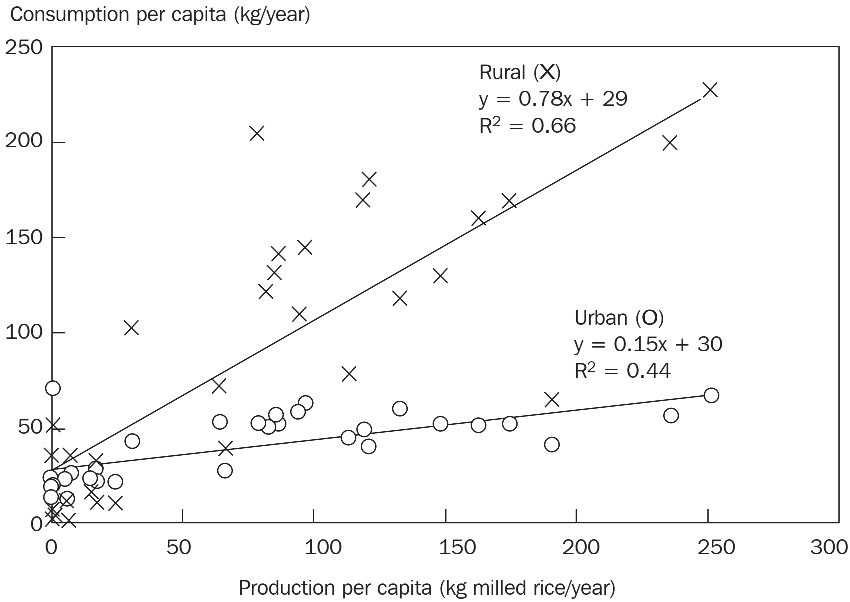

Fig. 14. Rural and urban rice consumption per capita as a function of rice production per capita, by province, China, 2005.

The data presented in this section show that estimating income elasticities even at a country level can lead to an aggregation bias. In Indonesia, the bottom two rural quintiles increased their rice consumption by 44% and 57%, respectively, between 1967 and 2006. Yet, between the same years, the top urban quintile decreased its consumption by 47%. Similar patterns exist in other countries, where we have data spanning more than 20 years, that is, India and Bangladesh. In Indonesia, rice consumption per capita for the whole country fell by 6% in 39 years, during which time real per capita income grew by more than 400%. Calculating an income elasticity using these figures would lead to an estimate of about zero (–0.015). Yet, clearly such an estimate is not a good guide to the future, as even the poorest rural quintile now has a negative income elasticity, as evidenced in Figure 12. Per capita rice consumption will decline sharply in the future in Indonesia, provided income continues to grow, as evidenced by the declines that have already taken place. Similar statements can be made for India and Bangladesh, although the magnitude of the declines in these countries is smaller so far because they are poorer (Fig. 16). But, both countries have been growing rapidly for the past decade, and appear poised to continue doing so.

These results from analyzing the disaggregated data on rice consumption strongly support the basic econometric findings from the time-series analysis of rice consumption. Except marginally in rural areas, income growth is no longer an important driver of higher rice consumption. In most areas, the move from rural to urban jobs will mean lower rice consumption, perhaps sharply lower. In several important rice-consuming

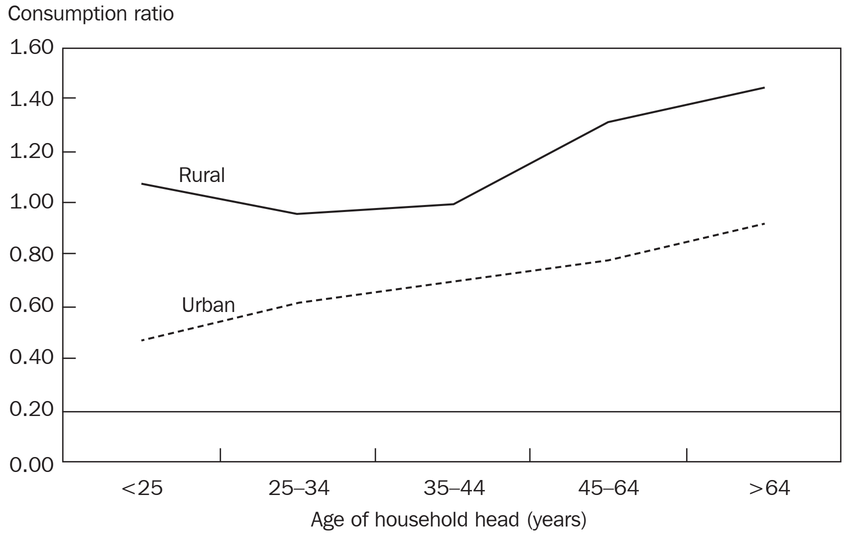

Fig. 15. Ratio of rice to wheat consumption in Malaysia by age of household head, 1998-99. Source of raw data: Department of Statistics, Malaysia (1999).

countries in Asia, there has been a steady drift downward over time in the whole Engel function, after peaking a decade or two ago. Each of these trends has important implications for projections of rice consumption in 2020, 2030, and 2050, the topic of the next section.

Projections of rice consumption in 2020, 2030, and 2050

As noted, we propose three alternative methodologies for projecting rice consumption, with an emphasis on the global totals for 2020, 2025, 2030, and 2050. The three models—baseline, structural, and best judgment—have strengths and weaknesses and we compare the results when introducing our own judgments about appropriate parameters for the projections. The details of the methodological assumptions, projections of independent variables, and resulting consumption projections are shown in Table 5.

A summary of the results is shown in Table 6 and in Figure 17, along with a comparison of our projections with some other projections in the literature. Figure 18 shows the 95% confidence intervals for our "best judgment" projections. All three of our projections show a modest increase in rice consumption between 2010 and sometime in the 2020s, and then a striking *decline* in the global consumption of rice between about 2025 and 2050. Even the baseline projection has global rice consumption declining by 0.51% per year over the 40-year period. Peak rice consumption is between 2020 and 2030, depending on how rapid is the rate of economic growth. Table 7 provides a summary of the key assumptions that drive our projections. The increasingly negative income elasticities under all three of our projections are notable.

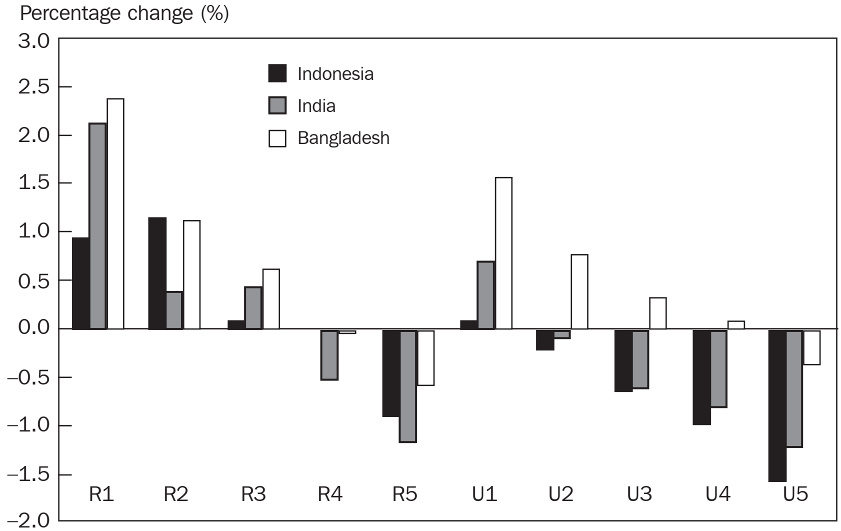

Fig. 16. Annualized percentage change in rice consumption by quintile and location, Indonesia, India, and Bangladesh. R refers to rural quintiles, U to urban quintiles. Periods over which changes are calculated are 1967-2006 for Indonesia, 1983-2005 for India, and 1983-2005 for Bangladesh.

Our projections are much lower than those made by most others in recent years, mainly because of these increasingly negative income elasticities. This difference is not explained by changes in population projections: the 2008 UN projection for 2050 global population is only slightly lower than that made in 2000. And, changes in assumptions about long-term economic growth rates are not directly an important determinant of the differences—*it is the income elasticity rather than the rate of economic growth that is driving our results*. In this regard, it seems likely that some of the earlier studies did not fully take account of declining per capita consumption in China and India, as these trends have become very pronounced only recently.[6] While we project lower rice demand than most studies, our projections are similar to those of Smil (2005), who estimated that total rice demand might increase by only 5% between 2004 and 2025. Table 7 shows how our projections are being driven by slower population growth, rural to urban migration, and declining income elasticities.

We then seek at least preliminary insights into where rice consumption will take place. These insights are informed by fairly detailed analysis of rice consumption in Asia, which historically has produced and consumed more than 90% of the total (the detailed country-specific econometric estimates are available from the authors). In addition, we analyze separately the shares of each major geographical region in global

[6] Rice consumption in India is expected to increase in 2010 as a result of major new efforts to reach the poor with subsidized rice. The trend decline is likely to continue after this effect becomes permanent, and the decline will be faster if the food distribution programs turn out to be temporary.

Table 5. Projections of world rice consumption, based on various alternative income growth rates and changes in the rate of rural-urban migration.[a]

Item	2010 base	2020	2030	2040	2050
Population, billion[b]	6.83	7.56	8.20	8.75	9.20
Time trend, 1.5% per year, kg per capita (increment from 2010)	–	10.37	22.41	36.38	52.59
Implied per capita consumption	64.61	74.98	87.02	100.99	117.20
Per capita income growth (US$):					
1.5% per year	6,152	7,140	8,286	9,617	11,160
Increment to per capita rice consumption relative to 2010, kg/year					
"Pure" income effect[c]		–0.92	–3.78	–8.41	–14.33
Trend agpopshr[d]		–2.11	–3.95	–5.38	–6.31
Faster agpopshr		–3.13	–5.82	–7.86	–9.15
2.0% per year (US$)	6,152	7,500	9,142	11,140	13,585
Increment to per capita rice consumption relative to 2010, kg/year					
"Pure" income effect		–4.66	–12.09	–21.15	–30.71
Trend agpopshr		–1.99	–3.41	–4.16	–4.26
Faster agpopshr		–2.95	–5.03	–6.09	–6.18
Global rice consumption, kg per capita per year, and total in million tons					
Income growth of 1.5% per year					
Trend agpopshr		61.58	56.88	50.82	43.97
[global total]		[465.5]	[466.4]	[444.7]	[404.5]
Faster agpopshr		60.60	55.01	48.34	41.12
[global total]		[457.8]	[451.1]	[422.9]	[378.3]

Table continued.

Table continued.

Income growth of 2.0% per year					
Trend agpopshr		57.96	49.11	39.30	29.64
[global total]		[438.2]	[402.7]	[343.8]	[272.7]
Faster agpopshr		57.00	47.50	37.37	27.72
[global total]		[430.9]	[389.5]	[327.0]	[255.1]
Summary projections, global rice consumption in million tons per year					
"Baseline": slow growth with rural to urban migration on trend					
	441.3	465.5	466.4	444.7	404.5
"Structural": rapid growth with accelerated rural to urban migration					
	441.3	430.9	389.5	327.0	255.1
"Best judgment":					
	441.3	450.0	430.0	385.0	330.0

[a]Based on model in column 5, Table 2. [b]Projections from U.S. Census Bureau. [c]Agpopshr (agricultural population share) held constant. [d]Note: "trend rate" is the same as the decline of 0.4 percentage points per year from 1960 to 2010; "faster" is a rate of decline of agpopshr of 0.6 percentage points per year.

Table 6. Projected global total rice consumption by three techniques, 2020-50, and comparison with other projections. Projections in million tons of milled rice.[a]

Source	2020	2025	2030	2050
FAO (2003)	–	–	535	–
FAO (2006)	–	–	503	522
Rosegrant et al (2001)	503	–	–	–
Sombilla et al (2002), low yield growth scenario	–	481	–	–
Sombilla et al (2002), baseline	–	516	–	–
Sombilla et al (2002), high yield growth scenario	–	562	–	–
Ito et al (2005), Scenario 1	–	479	–	527
Ito et al (2005), Scenario 2	–	443	–	461
Ito et al (2005), Scenario 3	–	385	–	383
Authors' baseline	466	469	466	404
Authors' structural	431	414	390	255
Authors' best judgment	450	440	430	360

[a]Projections are based on model 5 in Table 2. See Table 5 for details.

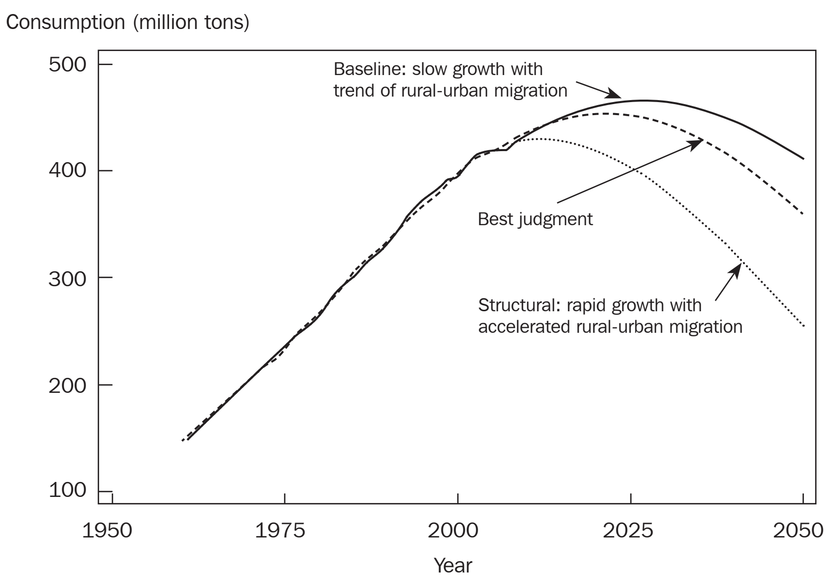

Fig. 17. Alternative projections of world rice consumption at different rates of economic growth and rural-to-urban migration, with real rice price constant at 2007 level.

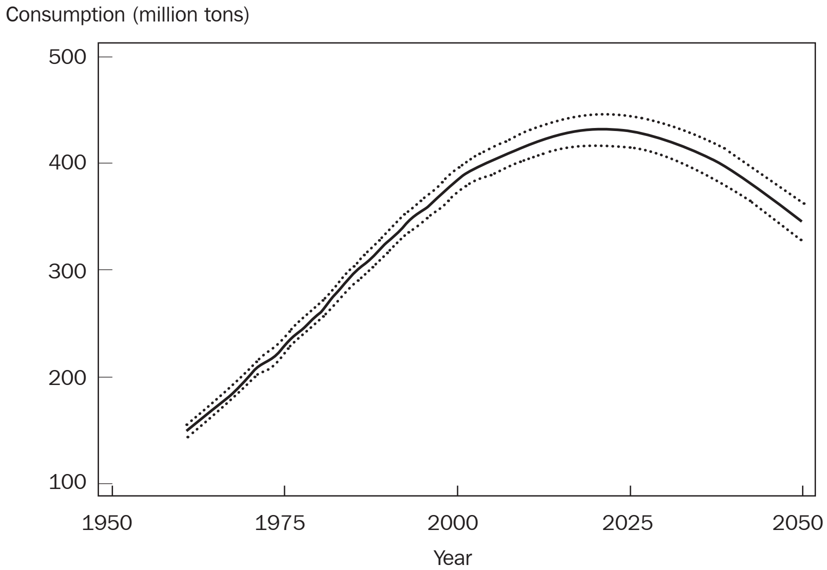

Fig. 18. Best judgment projection with 95% confidence intervals.

Table 7. Assumptions behind the projections.

Year	Population growth (%/year)	Rural-to-urban migration (agricultural population share)		"Net" income elasticity (combined effect of income and time trend)		
		Trend	Fast	Baseline	Structural	Best judgment
2020	1.02	0.34	0.32	–0.09	–0.33	–0.2
2025	0.99	0.32	0.29	–0.24	–0.55	–0.4
2030	0.77	0.30	0.26	–0.35	–0.68	–0.5
2050	0.58	0.22	0.14	–0.50	–0.73	–0.6

rice consumption. The surprise, perhaps, is how fast the share of rice consumption in Asia is likely to fall, and how important Africa may be in the global rice economy in less than half a century (although Asian consumption will still account for nearly 80% of the total in 2050).

Tables 8 and 9 show two alternative ways to project regional rice consumption. A "naïve" approach is used in Table 8, with each of four regions (Asia and the Middle East, Africa, North and South America, and the residual "rest of the world") having its own consumption explained by time and time squared. The results show the power and the weakness of this naïve approach, as sharply different time paths of rice consumption emerge. Rice consumption in Asia and the Middle East falls by 0.58% per year from 2010 to 2050, whereas it grows by 3.92% per year in Africa.

These sharply divergent paths create a serious problem of consistency between the sum of the individual regional projections, which reach 456.7 million tons in 2050, and the directly estimated total of global rice consumption (using the same naïve time-series approach), which reaches only 389.7 million tons. The sum increases by 0.26% per year from 2010 to 2050 whereas the directly estimated total actually falls by 0.31% per year. The different result arises because Africa, modeled separately, has a rapidly rising trend of rice consumption that shows no sign of slowing (thus the lack of a significant quadratic coefficient in Table 4). When Africa is included only as part of the global aggregate, this rapidly increasing trend is buried in the aggregate (just as canned tomato juice was buried in the aggregate of total processed tomato consumption, in the earlier lesson). In reality, we do not expect that African rice consumption will continue to increase for the next 40 years at a constant and rapid exponential rate. Such a scenario would be likely to create such high levels of import dependency that they could not be supported politically or financially.

To correct for this inconsistency, we take a more sophisticated approach. We model global rice consumption according to the two basic models, baseline and structural. These results are shown in Table 9. Separate share regressions are then used to project the share of each region in global rice consumption; the estimated shares are shown in brackets for each year and region in Table 9. This technique maintains a sharp fall in the share of Asia and the Middle East in global rice consumption—from 88.4% in 2010 to 78.5% in 2050. The sharp rise in Africa's share also continues to show up in this approach; it rises from 5.9% in 2010 to 13.1% in 2050.

With this adjustment, the calculated regional totals of rice consumption for each projected year are more reasonable. Implied rice consumption in 2050 for Africa is 33.3–52.8 million tons instead of the 108.0 million tons projected in the direct naïve approach. The rate of growth is still quite rapid over the 40 years—between 0.63% and 1.80% per year. The amount of rice consumed in Asia and the Middle East falls significantly, between 0.51% and 1.65% per year for the same period. Rice consumption in the Americas continues to increase under the baseline projection, but falls slowly under the structural model incorporating rapid economic growth.

Finally, our own judgments on the future of rice consumption recognize the likely consumption impact of the rapid movement of workers from rural to urban areas in major rice-producing regions, and of the rapid pace of decline in income elasticities of demand for rice. Still, we believe that the structural model with rapid economic growth may exaggerate their impact, if only because cultures and tastes change slowly. Our best guess, based on all the analysis so far, is that rice consumption in 2050 will be about 360 million tons, with 270 million tons of that in Asia, about 35 million tons in the Americas, and as much as 55 million tons in Africa. We are, however, highly uncertain about the Africa projection, and, because of that uncertainty, about the overall level of rice consumption globally. If, for example, Africa turns out to grow rapidly in both income and population, and continues to substitute toward rice and away from traditional food staples, it seems possible that consumption on the continent could exceed 100 million tons by 2050. Global consumption might then be as high as 405 million tons according to our "best judgment" projections, still less than in 2010.

Table 8. "Naïve" projections of rice consumption by region and globally (using directly estimated regressions with time and time squared), 2010-50, million tons of milled rice.[a]

Year(s)	Asia and Middle East	Africa	North and South America	Rest of world	Sum	Global total[b]
2010	390.1	23.2	24.5	3.9	411.7	441.3
2020	402.7	34.1	28.8	3.6	469.2	465.2
2030	391.5	50.1	32.8	3.1	477.5	463.7
2040	358.4	73.5	35.9	2.5	470.3	437.1
2050	308.9	108.0	37.9	1.9	456.7	389.7
Average annual % change						
2010-20	0.32	3.93	1.63	–0.80	1.32	0.53
2010-30	0.02	3.92	1.47	–1.14	0.74	0.25
2010-50	–0.58	3.92	1.10	–1.78	0.26	–0.31

[a]Projections based on time-series regressions from 1960 to 2008 using time and time squared as independent variables. See Table 4 for details. Only time was significant for the Africa regression. [b]Global total estimated directly from simple time-series regression.

Table 9. Projections of rice consumption by region using global totals from the baseline and structural regressions, and then applying the share regressions to allocate the total among the regions, 2010-50, million tons of milled rice.[a]

Year(s)	Asia and Middle East baseline	Asia and Middle East structural	North and South America baseline	North and South America structural	Africa baseline	Africa structural
2010 base	390.2 (0.884)	390.2	25.1 (0.057)	25.1	25.9 (0.059)	25.9
2020	402.9 (0.866)	372.9	29.0 (0.062)	26.8	32.0 (0.069)	29.6
2030	393.2 (0.843)	328.3	31.9 (0.068)	26.6	40.2 (0.086)	33.6
2040	363.0 (0.816)	266.9	33.6 (0.076)	24.7	47.5 (0.107)	34.9
2050	317.7 (0.7854)	200.4	33.8 (0.084)	21.3	52.8 (0.131)	33.3
Average annual % change						
2010-20	0.32	–0.45	1.45	0.66	2.14	1.34
2010-30	0.04	–0.86	1.21	0.29	2.22	1.31
2010-50	–0.51	–1.65	0.75	–0.41	1.80	0.63

[a]Estimated shares of rice consumed by region are shown in parentheses. The same share is used for the baseline and the structural projections. Note that much of the rapid decline in rice consumption under the "fast growth" structural projection is likely to be in Asia, and this is not reflected in the table.

There is, of course, considerable uncertainty involved in these projections. For example, we have modeled the impact of incomes on per capita consumption as a quadratic function, which implies very low consumption in the very long term. In reality, the functional form is probably quadratic only over a range, and it may flatten out at some point instead of continually declining. Because per capita income is still low in many Asian countries, however, our current data do not allow for reliable estimation of this more complex functional form that may become relevant only at significantly higher levels of income (although the evolution of rice consumption in Japan is consistent with the story we tell here, and we use nonparametric estimates of the Engel elasticity in our "best judgment" projections). In addition, Figure 6 shows clearly the tremendous heterogeneity of different country experiences with respect to turning points in per capita consumption, and our projections gloss over this diversity.

Further, declining rice consumption does *not* imply that research to raise the productivity of rice production and marketing should also decline. First, research expenditures should be directed primarily to sectors where rates of return are high, and the literature on returns to agricultural research shows that these rates of return have typically been very high (well above the opportunity cost of capital). Reducing the amount of global rice production that such research would apply to by 20% (compared with current production levels) is not likely to fundamentally alter the profitability of investments in rice research—rice will still be the developing world's most important food crop in 2050. Second, simply maintaining existing levels of rice productivity in the face of environmental degradation and impending climate change will require a massive research effort, and reduced rice consumption 30–40 years from now may allow rice scientists to concentrate their efforts on increasing yields in the most ecologically suited areas for rice, thus avoiding further encroachment on forests, dry upland areas, and coastal zones. And, third, rice consumption and production are likely to be even more concentrated among the poor in the future, given the negative income elasticity of demand. If spending on public goods is to be targeted preferentially to the poor, this is another strong argument for continued investment in rice research.

Three remaining questions have not been addressed in this research (in addition to addressing the great uncertainty over future rice consumption in Africa). First, we have focused entirely on the quantity of rice consumed and have discovered a notable tendency for this to decline at higher income levels. However, we know that the quality of rice demanded is also a function of income, with a strong positive effect. Some of this consumer demand for higher quality rice can be captured by farmers through the varieties they grow and the postharvest procedures they adopt. Some must be offered by the marketing system, through improved milling, storage, and packaging. And, some will be captured at the point of sale through improved service and shopping conditions.

The private sector will need to take the lead in meeting this future demand for higher quality. Higher quality rice will obviously be consumed primarily by higher income consumers; furthermore, production and trading of any new high-quality varieties will likely be done disproportionately by better-off farmers and traders. Thus, the role of the public sector in meeting the demand for higher quality rice should be somewhat limited and focused on technologies that will generate benefits for the poor, either through higher incomes for poor farmers or lower prices for poor consumers.

The second question is, where will consumers buy their rice and how will supply chains evolve to procure and distribute it? The "supermarket revolution" that has swept Latin America and much of Asia may well change where and how consumers access their daily rice supplies (Reardon and Timmer 2007). Virtually no research has been done on the implications of this change for levels of rice consumption, structure of the rice marketing system, rice price stability, or food security in those countries heavily dependent on rice.

Third, available models of climate change and its impact on crop production by region and commodity suggest far-reaching changes that would alter (1) relative costs of rice production compared with its major cereal competitors, and (2) influence in which locations it will remain feasible to continue to grow rice (Nelson et al 2009). The ultimate impact on rice consumption is, of course, highly conjectural. Any such impact would presumably have to work primarily through changes in relative prices, and none of our three sets of rice consumption projections incorporates changes in prices, mostly because the estimated price coefficients are very small and of low statistical significance. Still, the climate change models do suggest that relative prices of rice to wheat and maize could change significantly by 2050.

Based on crop-specific and region-specific projections of rice and wheat production with and without climate change, IFPRI's model of the world food economy, for example, suggests that the relative price of rice to wheat will rise from 1.44 in the base year of 2000 to 1.88 in year 2050 without significant climate change, and to 1.63 in year 2050 with the climate change predicted by the National Center for Atmospheric Research (NCAR) model (with no carbon fertilization effect). These relative prices result from IFPRI's projections that real prices of rice (in 2000 US$) will rise from $180 per ton in 2000 to $310 per ton in 2050 without climate change, and to $440 per ton with climate change. By contrast, wheat prices rise from the base-year figure of $125 per ton to $165 per ton in 2050 without climate change, and to $270 per ton with climate change. Thus, the impact of climate change *alone* is to lower the relative price of rice to wheat by 13.3% in 2050, although both 2050 scenarios have the *real* price of rice rising significantly, by 72% and to 144%, respectively, without and with climate change (Nelson et al 2009). An additional uncertainty from the potential for climate change comes from possible global actions to tax agricultural activities that are large emitters of greenhouse gases, with traditionally grown rice a prime target. Any tax on rice production would raise its cost of production and likely market price, thus further driving down consumption.

Determining the impact of these potential price changes on global rice consumption in 2050 goes beyond judgment to pure speculation. If we apply long-run price elasticities of demand for rice of –0.03 to –0.10, which are consistent with the econometric evidence presented earlier, rice consumption in 2050 would be 2.2% to 14.4% less than we otherwise project in Tables 5 and 6. A range of 330 to 340 million tons for the "judgmental" projection is implied, instead of the 360 million tons shown in the table. Offsetting this further decline in rice consumption would be the *relative* decline in the price of rice compared with wheat, projected to be 13.3%. Even if the cross-price elasticity of demand is 0.2, rice consumption would rise by only about 2.7% because of the relatively higher wheat price. Perhaps a reasonable speculation is that rice consumption would be about 350 million tons in 2050 when likely price effects are accounted for, an amount slightly less than the global total of rice consumption projected without price effects.

Offsetting this relatively small impact projected from climate change is the realization that much of the impact for rice versus wheat would come in South Asia, where both wheat and rice are consumed regularly and where the relative impact of climate change is projected to be quite large. As the NCAR model shows, rice production in South Asia is projected to be 14.5% lower in 2050 with climate change than without, whereas wheat production in the same region is projected to be 48.8% lower (Nelson et al 2009). Thus, there could be large shifts in relative consumption patterns in this region.

In closing, most readers are likely to be surprised by the momentous changes in rice consumption projected in this chapter. Underlying the dynamics of these changes, however, is one more manifestation of Bennett's Law, originally formulated in 1954 (Bennett 1954), which argues for an inherent desire for dietary diversity as incomes rise. Thus, the desire of most Asian consumers to have a more balanced diet than what has traditionally been available to them, especially in rural areas, is not unusual. It is common for rural Asian consumers to get 70% of their daily calories from rice—it was the only food staple that could be grown intensively in their agro-climatic environment. As rising incomes, more open trade, and global communications present the opportunity to diversify their diets, we should not be surprised that they respond.

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The global rice supply and demand outlook: the need for greater productivity growth to keep rice affordable

Samarendu Mohanty, Eric Wailes, and Eddie Chavez

Introduction

Global rice production and consumption are highly concentrated in Asia, where rice is a basic staple for most of its inhabitants. Around 90% of world rice is produced and consumed in the region. Before the 1970s, most Asian countries struggled to feed their rapidly expanding population because of frequent occurrence of famine and drought. Per capita grain production in Asia was 194 kg in 1961 compared with 868 kg for the U.S. (FAOSTAT). However, the food situation improved dramatically throughout Asia since the 1970s, with the development of high-yielding varieties. By 1980, rough rice yield reached 2.8 t/ha as compared to 1.8 to 2.0 t/ha before the introduction of modern varieties. Yield increased further by another 30% to 3.6 t/ha by 1990. By 2000, rough rice yield was hovering around 4.0 t/ha.

With the expansion of both area and yield, Asian rough rice production nearly doubled from 290 million tons in 1970 to around 545 million tons in 2000 (FAOSTAT). In some Asian countries such as India and the Philippines, rice production nearly doubled only two decades after the introduction of high-yielding varieties. However, annual yield growth of rice has declined to less than 1% in recent years compared with more than 2% growth during the first two decades of the Green Revolution period.

This slowdown in productivity growth combined with adverse weather in key rice-producing countries and rising demand arising out of economic development and population growth in developing countries have resulted in a drawing down of cereal stocks in recent years. For rice, global stocks declined from a 135-day supply to a 70-day supply in 7 years—a 44% drop from 147 million tons in 2001 to 82 million tons in 2008 (Fig. 1). During this period, rice prices nearly doubled as the major rice-exporting and -importing countries adopted trade-restrictive policies to limit domestic food price inflation, a behavior that reflected an unwillingness to rely on the global rice stock−depleted economy. Thus, even before the 2007-08 rice price spike, the market was primed for such an event, with stocks hovering around a level not witnessed in decades. Rising wheat and maize prices due to production shortfalls and the expansion of biofuel production put pressure on rice, which led to trade restrictions in many rice-producing countries and unprecedented rises in prices. During a span of 6 months, between November 2007 and May 2008, rice prices nearly tripled in the international market. As expected, rice prices have declined since reaching an all-time high in May 2008 but they still remain high relative to what they were just a few years ago.

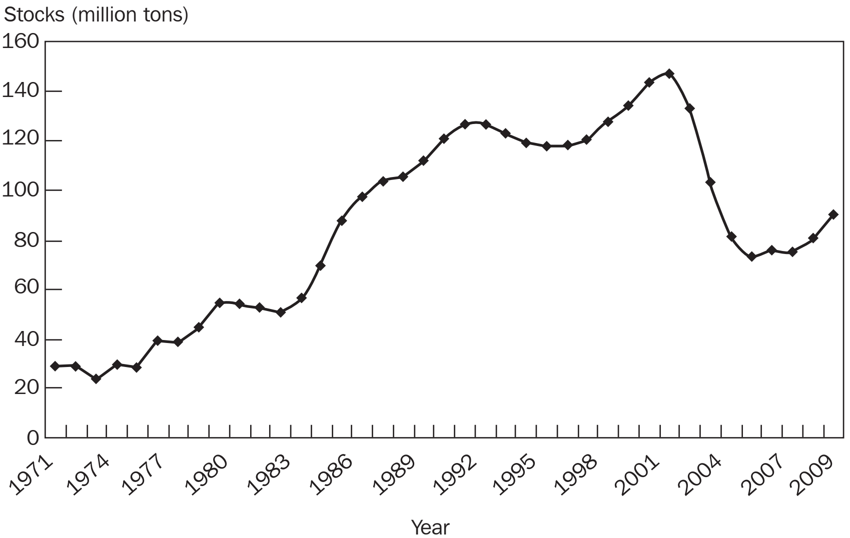

Fig. 1. Global rice stocks. Data source: USDA.

Despite a slight increase in rice supply for 2008-09, uncertainties are large regarding the source of future growth in global rice production. The recent crisis in the rice market has exposed the fundamental imbalance between supply and demand. The world has produced a record milled rice crop in each of the last four years, with 37% of the increase coming from area expansion rather than yield growth (USDA 2010). Current rice area is at a historic high and it is unrealistic to assume that additional area can continue to meet future demand. From a future rice food security perspective, it is absolutely essential to examine future supply and demand growth under different situations and adopt appropriate measures to eliminate the supply-demand imbalance to be able to achieve global rice food security and ensure that rice is available to the most vulnerable section of society at an affordable price.

This chapter aims to develop a medium-term global supply and demand outlook for rice and simulate the impacts of greater productivity growth to draw policy implications for future global rice food security. The baseline outlook is developed using the Arkansas Global Rice Model for the major rice-producing and -consuming countries under a set of assumptions regarding population, income, exchange rate, and other macro-assumptions. The medium-term supply and demand outlook will be augmented by adding discussions on long-term supply and demand projections developed by the International Food Policy Research Institute (IFPRI) and the Food and Agriculture Organization (FAO) of the United Nations. Following this, a scenario is developed to determine the supply growth that will be needed to keep the rice price affordable at US$300 per ton for the next ten years. Finally, policy implications are discussed along with brief conclusions.

The Arkansas Global Rice Model

In this chapter, a medium-term supply and demand outlook is developed using the Arkansas Global Rice Model (AGRM) managed by researchers at the University of Arkansas. This model has been extensively used for medium-term market outlook and policy analyses in the United States and other parts of the world.

The AGRM is a partial-equilibrium structural econometric simulation model. It includes major rice-producing, -consuming, and -trading countries and can be divided into six subregions: Americas, South Asia, North Asia, the Middle East, Africa, and Europe (Wailes and Chavez 2009). Several countries are included in each region: (1) the Americas has the United States, Canada, Argentina, Brazil, Mexico, and Uruguay; (2) South Asia has Australia, India, Indonesia, Pakistan, Bangladesh, Malaysia, Myanmar, Thailand, Vietnam, and the Philippines; (3) North Asia has China, Taiwan, Japan, Republic of Korea, and Hong Kong (China); (4) the Middle East has Iran, Iraq, Saudi Arabia, and Turkey; (5) Africa has Egypt, Côte d'Ivoire, South Africa, Nigeria, and other African countries; and (6) Europe has the EU-27. The specific countries included in the model account for 84% of world rice production, 82% of consumption, 86% of world rice exports, 80% of world rice imports, and 83% of world rice stocks (Wailes and Chavez 2009). In addition, the model also differentiates the rice market into two broad market groups, long grain and medium/short grain.

As shown in Figure 2, the representative country model includes supply, demand, and trade; ending stocks; and market equilibrium conditions. Rice production is modeled by estimating separate area and yield equations. The model incorporates

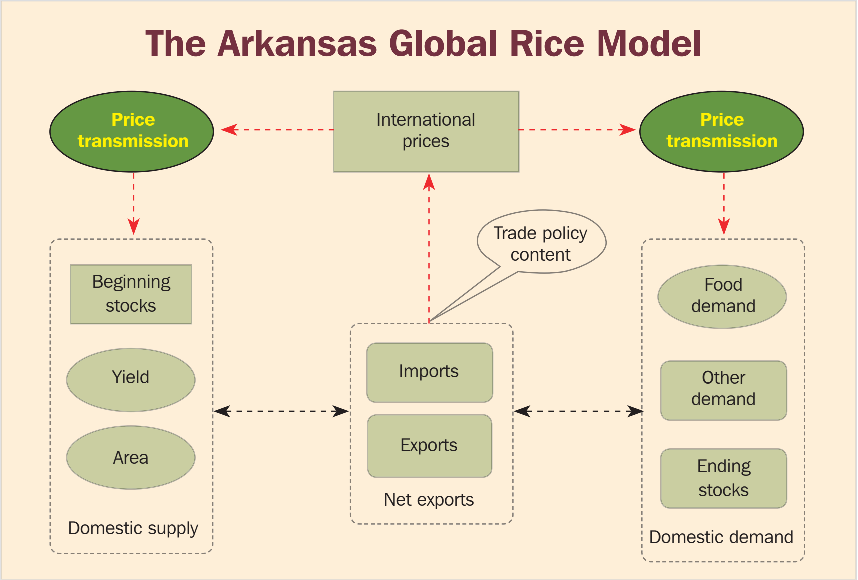

Fig. 2. Representative rice model for long grain/medium grain.

the regional supply response of rice and different competing crops in some producing regions. For example, the U.S. model includes state/regional area and yield response with rice production divided into six regions: Arkansas, California, Louisiana, Mississippi, Missouri, and Texas. Similarly, for China, the rice supply is divided into long-grain and medium-grain rice. On the demand side, rice consumption is divided into food, seed, and other uses. Individual country models are then linked through net trade equations to solve Thai FOB (100B, Bangkok) to appropriately link an individual country to the world rice economy (Wailes and Chavez 2009). Since the rice market is heavily distorted, the model explicitly includes policy variables in supply, demand, ending stocks, exports, imports, and price transmission equations.

On the supply side, rice area is specified as a function of the previous year's harvested area, expected price or gross returns received by producers for rice and competing crops, and expected input price. Specifications vary by country but in general partial adjustment expectations from the previous year are the most representative. Yield is specified as a function of expected output, input prices, and technological change, based on R&D expenditures or trend assumptions. On the demand side, per capita food consumption is specified as a function of real per capita income, real rice retail price (weighted average of the free market price and government ration price), and substitute food prices. The export demand equation is specified as a function of the difference between domestic production and consumption and export price. Finally, the ending stock is calculated, in general, as the residual to close the national model. For the major exporting countries, export demand is calculated as the residual to close the model. The data set used in this study was compiled from various sources, including the Food and Agricultural Policy Research Institute (FAPRI) for the historical and projected macro variables (real GDP, exchange rate, population, CPI, and GDP deflator); the Production, Supply, and Demand (PS&D) database of the U.S. Department of Agriculture, for rice area, yield, production, domestic consumption, ending stocks, and trade; and the Rice Situation and Outlook Yearbook for U.S. and global rice prices. All these equations were estimated using econometric techniques. For more information on parameter estimates and diagnostic statistics, please see the model documentation by Wailes and Chavez (2009).

The supply and demand elasticities calculated from the estimated parameters are reported in Tables 1 and 2, respectively. These estimates are derived from either linear or double-log equations. Supply elasticities refer to the price or returns incentive to produce. In many countries, this is conditioned by policies so that the response is to an effective (policy-distorted) price. Demand elasticities with respect to price refer to response to retail prices or, if unavailable, to wholesale prices. As shown in Table 1, rice area response elasticities range from 0.09 to 0.58, with a fairly inelastic supply response for major rice-producing countries such as India, China, Thailand, and Vietnam. As expected, income elasticities are negative for most rice-consuming countries in Asia, with the exception of India, the Philippines, and Malaysia. However, income elasticities of rice are positive for most rice-consuming countries in the Americas, Europe, the Middle East, and Africa.

Table 1. Rice supply elasticities (area harvested with respect to net returns/effective price received by farmers).

Country	Supply elasticity	Country	Supply elasticity
United States		China	
Arkansas	0.122	Indica	0.155
California	0.170	Japonica	0.155
Louisiana	0.117	Taiwan	0.007
Mississippi	0.183	Côte d'Ivoire	0.577
Missouri	0.147	EU-27	0.320
Texas	0.149	Iran	0.001
Thailand	0.193	Iraq	0.349
Vietnam	0.232	Pakistan	0.381
Australia	0.170	Argentina	0.112
Bangladesh		Brazil	0.070
Aman	0.093	Mexico	0.097
Boro	0.186	Uruguay	0.150
India	0.108	Republic of Korea	0.125
Indonesia	0.103		
Malaysia	0.429		
Philippines	0.152		

As expected, as a basic staple for most Asians, the own price response of rice demand is found to be highly inelastic. This has been evident in the past two years, with a negligible impact on demand despite the doubling of rice prices.

The supply and demand outlook

A 10-year global rice supply and demand outlook was developed for marketing years 2008-09 to 2018-19 under a given set of macro projections (income, exchange rates, inflation, and other input markets) developed by IHS Global Insight. In addition, the baseline projections assume a continuation of current policies, normal weather, and trend yield growth. The simulation results suggest that global per capita rice consumption, following its recent trend, will decline from 64.5 kg in 2008-09 to 63.7 kg in 2018-19. Rapid economic growth, urbanization, and other long-term social and economic transformations in many Asian countries are likely to change consumer demand patterns toward the consumption patterns of developed countries. Among the major rice-consuming countries, both Chinese and Indian per capita consumption during this period is projected to decline by 5.2 and 1.2 kg, respectively. Nevertheless, even with such a decline in per capita rice consumption, total consumption in these two countries is projected to increase by 13 million tons because of population

Table 2. Rice demand elasticities.

Country	Own price	Income	Country	Own price	Income
United States	–0.005	0.386	China	–0.100	–0.070
Thailand	–0.100	–0.170	Hong Kong	–0.176	–0.185
Vietnam	–0.190	–0.050	Taiwan	–0.012	–0.026
Australia	–0.108	0.432	Côte d'Ivoire	–0.550	0.135
Bangladesh	–0.040	–0.635	EU-27	–0.200	0.380
India	–0.150	0.100	Iran	–0.350	0.210
Indonesia	–0.139	–0.060	Iraq	–0.100	0.140
Malaysia	–0.302	0.153	Pakistan	–0.175	0.070
Philippines	–0.148	0.088	Saudi Arabia	–0.253	0.050
Japan	–0.113	–0.255	Argentina	–0.071	0.111
Egypt	–0.274	–0.040	Brazil	–0.150	–0.050
Nigeria	–0.300	0.350	Mexico	–0.050	0.259
Turkey	–0.150	0.001	Uruguay	–0.240	0.700
			Republic of Korea	–0.704	–0.338

growth. Overall, China's and India's share in total world consumption is projected to fall from 52% in 2008-09 to 50% in 2018-19. For many developing Asian countries such as Bangladesh, Vietnam, Indonesia, and Malaysia, per capita rice consumption is projected to decline as the people diversify into a diet with more protein with a rise in income. Per capita consumption in several higher-income countries such as Republic of Korea, Thailand, Taiwan, and Japan is projected to continue to decline, albeit at a slower rate, over the next ten years. The only two exceptions in Asia are the Philippines and Myanmar, where a modest increase in per capita consumption is projected in the next ten years.

Unlike in Asia, per capita rice consumption is projected to rise in many other countries in the Middle East, Africa, Europe, and the Americas. In the United States, per capita rice consumption is projected to increase by 6% in the next ten years primarily because of immigration from Asian countries and food diversification. A similar trend is projected in Mexico, Brazil, and other South American countries. Following the historical trend, strong per capita consumption growth is projected in many Middle Eastern and African countries. Overall, 45 million tons of additional milled rice, equivalent to around 68 million tons of rough rice, will be needed by 2018-19 above the 2008-09 consumption of 432 million tons (Fig. 3).

On the supply front, global rice harvested area is projected by the AGRM to decline slightly from the 158 million ha in 2008-09 because of competition from nonagricultural uses and shifts to other crops. Significant area contraction in China will be partially offset by some increases in area in other Asian countries, but not enough to keep global rice area at the level witnessed in 2008-09. The decline in area, combined with a significant slowdown in yield growth, around 8.7% in ten years, results

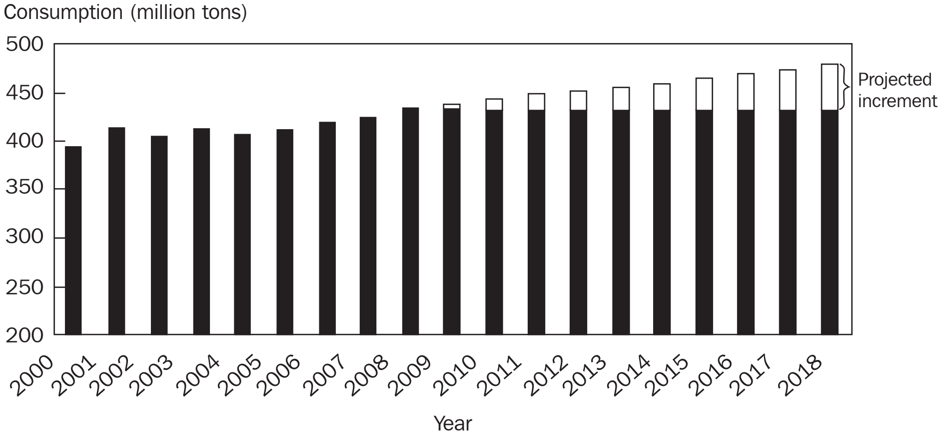

Fig. 3. Projected global milled rice consumption.

in production of 475 million tons by 2019 compared with 440 million tons in 2008. For the majority of the projection period, supply growth lags behind demand growth with the drawing down of the global rice inventory to meet the deficit. Rice stocks are projected to decline from 85 million tons in 2008-09 to around 73 million tons in 2018-19. The rice price for Thai 100%B in nominal terms is projected to continue its downward trend until 2010-11 from the historic high of 2008-09. For the remaining projection period, the price is projected to rise steadily from $390 per ton in 2011-12 to $526 in 2018-19, an increase of 35%, as consumption outstrips production, causing frequent dipping into the buffer to meet the imbalance.[1] Although beyond the scope of the model, the rising rice price is likely to be accompanied by greater volatility because of declining buffer stocks.

The long-term outlook

Over the longer term, diversification of the food basket is expected to continue from rice to other high-value products, including fruits, vegetables, and livestock products, as the developing countries get wealthier. FAO (2006) estimates per capita rice consumption to decline to 62 kg by 2030 and further to 59 kg by 2050. For the developing world, per capita rice consumption declines from 78 kg in 2000 to 72 kg in 2030 and 67 kg in 2050. Unlike FAO, IFPRI 2050 baseline projections developed by Nelson et al (2009) using the IMPACT model paint a significantly different picture for rice. Based on this report, 2050 per capita world rice consumption for the baseline is projected to be around only 49.7 kg (calculated by dividing IFPRI's 2050 world rice production of 455.2 million tons by the UN population projection). Despite declining rice consumption, both of these studies project per capita cereal consumption to rise in the

[1]Other medium-term baseline projections by FAPRI, USDA, and OECD-FAO show similar international rice price paths (Mane and Wailes 2010).

next four decades. According to FAO, per capita cereal consumption is projected to increase from 309 kg in 2000 to 339 kg in 2050, with coarse grain accounting for most of the increase. According to IFPRI's baseline projection of no climate change, per capita cereal consumption is projected to rise from 275 kg in 2000 to 287 kg in 2050 (calculated from the production numbers reported by IFPRI for rice, wheat, maize, millet, and sorghum divided by UN population numbers). Despite some decline in per capita rice consumption, total consumption is projected to rise because of population growth. The FAO study projects total rice consumption to rise by 35% from 387 million tons in 2000 to 522 million tons in 2050, while the IFPRI projection increases total consumption by only 16%.

On the supply side, IFPRI projects rice production to be 455 million tons in 2050, with Chinese production declining by 20 million tons from its 2000 level. Other East Asian countries also follow the Chinese pattern with a decline in production from the 2000 level. During this period, India accounts for a slight increase in production, whereas a significant increase is projected in other South Asian countries. Rice production in sub-Saharan Africa (SSA) is projected to more than double by 2050. Similarly, rice production in Southeast Asian countries is projected to get a significant boost in the next four decades. Since the time-path of IFPRI's baseline projections is not published, it is difficult to say exactly when the reversal in supply trend will occur. Unlike in IFPRI estimates, FAO projects a healthy growth in rice supply, with production rising from 403 million tons in 2000 to 524 million tons in 2050, a 30% increase.

The uptrend in rice price seen in the medium-term outlook is reinforced by the longer-term price outlook developed by IFPRI. By 2050, the rice price in real terms is projected to increase by around 80% from the 2000 level.

From both medium- and long-term perspectives, it is clear that there is a mismatch between supply and demand growths for rice in the future. In the past, yield growth lagged behind consumption growth and area expansion provided supplemental production to meet global needs. But this is unlikely to continue in the future as area growth is expected to slow significantly and competition will be greater for rice area from both other agricultural (biofuels) and nonagricultural uses such as industrialization and urbanization. Rising water scarcity will also become an important challenge in current rice-producing/-exporting regions in the future, including the United States, Australia, Egypt, and China. In the face of limited or no additional area expansion, it is clear that yield growth will have to match demand growth if we want to keep rice affordable for millions of poor people around the world.

US$300 rice price scenario results

To assess the yield growth required to keep rice more affordable than in the most recent years, a simulation was conducted using the Arkansas Global Rice Model. In this simulation, yield growth was exogenously shifted to levels above the baseline projected yield growth to obtain a target constant nominal price of $300 per ton.[2] The price of $300 was chosen as it approximates the average of the 2005-06 to 2007-08 world reference price. Baseline rice yield is projected to grow by 8.7% in the next 10 years (Fig. 4). The projected rice price corresponding to this baseline scenario climbs to $530 per ton and stays at that level for the last few years of the projection period. The scenario results suggest that global rice yield needs to grow at a much faster rate of around 15% in the next 10 years to keep the price at around $300 per ton. Lower rice prices also take land out of rice production into other productive uses. For 2010-11, world rice area for the scenario is 1.3 million ha less than the baseline level of 155.3 million ha. The amount of area decline becomes bigger with time and, by 2018-19, the rice area for the scenario is 151.6 million ha compared with 155 million ha for the baseline (Fig. 5). As expected, lower prices will increase rice consumption, with per capita consumption higher by 0.6 to 1.4 kg annually over the same period (Fig. 6). Total consumption is projected to rise by 4.3 million tons in 2010-11 and the difference rises to 10.6 million tons by 2018-19.

In addition, the declining global rice inventory in the baseline period reverses its trend and is projected to rise from 95 million tons in 2010-11 to 118 million tons in 2018-19 (Fig. 7). This is a difference of 45 million tons of additional rice stocks by 2018-19 between the baseline and scenario results. The importance of global rice stocks is quite evident in the current market, in which prices are staying high to meet any expected eventualities despite record production in the major rice-growing countries. Lower rice prices also encourage countries to depend on imported rice and, by 2018-19, global rice trade is projected to be 9 million tons higher than the baseline level of 36 million tons. The increase in trade is also absolutely crucial for reducing price volatility, which affects the standard of living of millions of poor people around the world, particularly in the developing and least developed countries in Asia and Africa.

Concluding remarks

The Green Revolution has played a key role in the last 50 years in expanding rice production to offset the ever-increasing population in many food-deficit countries around the world. This has improved the nutritional intake of billions and has reduced child mortality and undernourishment of infants around the developing world. The benefits of a vibrant agricultural sector have also supported overall economic growth in many Asian countries over the years. The economic boom witnessed by developing Asia in the last two decades can be partly linked to cheap food during this period. But, things are not the same any more, and neglect of this sector is reflected in the slowdown in yield growth in recent years. Current rice yield growth has fallen below 1% and the

[2]Although this scenario estimates the yield growth differential for the next ten years, we by no means imply that this shift is immediately achievable. The purpose of the scenario is to highlight what would be required to make rice supplies more affordable for the world's impoverished populations, compared with our baseline scenario of a rising price path.

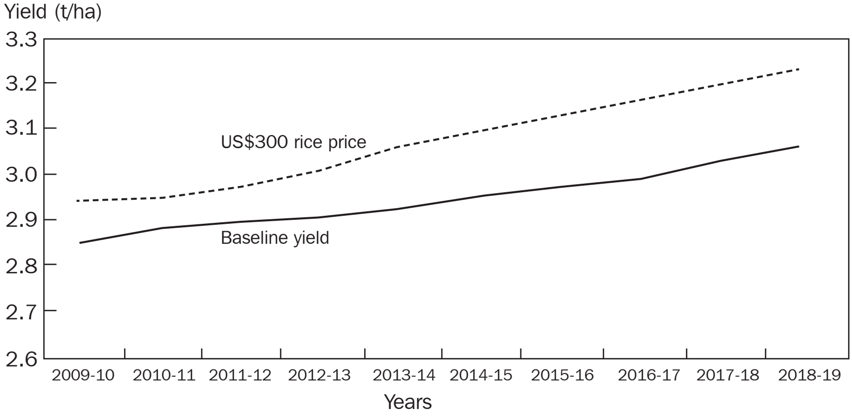

Fig. 4. Yield growth required to keep price at US$300/ton.

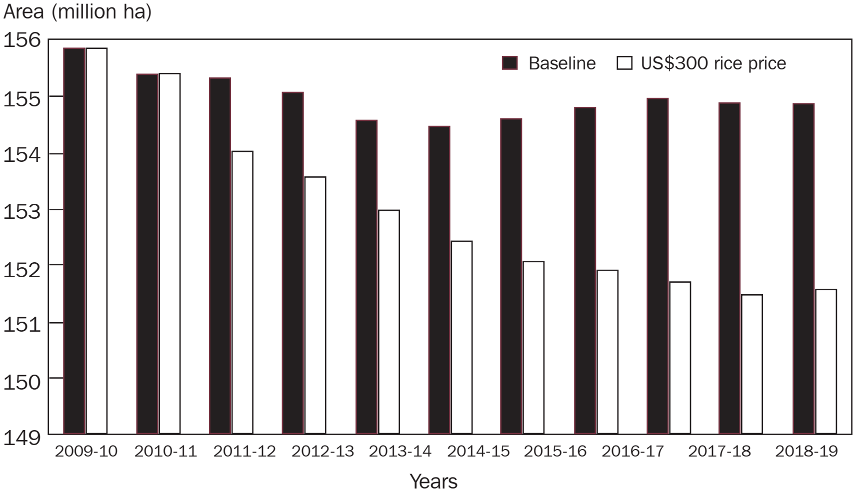

Fig. 5. Global rice area.

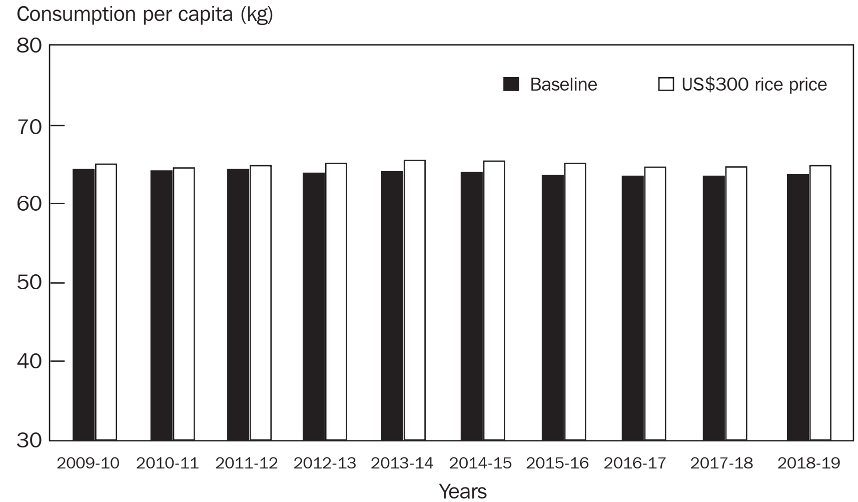

Fig. 6. Global per capita rice consumption.

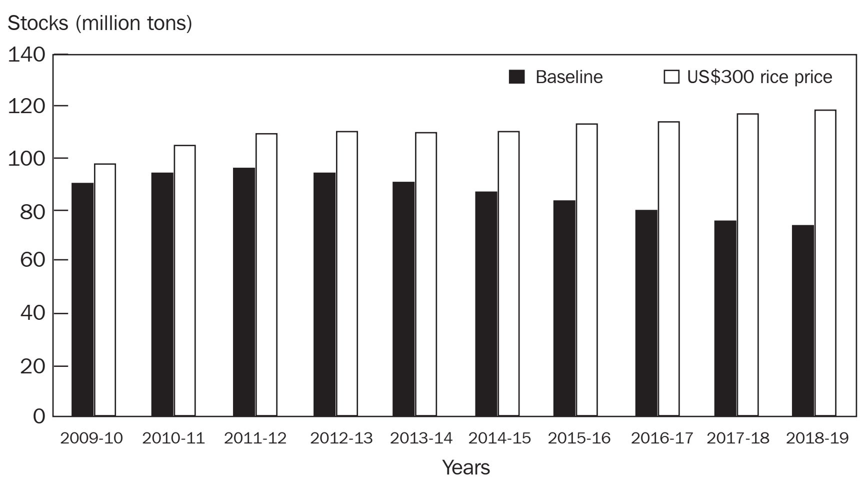

Fig. 7. Projected global rice stocks.

potential to get additional production growth from area expansion is highly unlikely if not impossible.

Looking ahead, global rice consumption remains strong due to population expansion and economic growth in many developing and least developed nations. Even with a decline in per capita consumption in many traditional rice-consuming countries in Asia such as China, India, Vietnam, Indonesia, and Thailand, global rice per capita consumption has remained more or less flat in the last decade. The decline in per capita rice consumption in many Asian countries is being offset by a rise in rice consumption in Africa, the Middle East, and many developed nations. This is likely to continue in the future as economies grow, and global rice consumption per capita is likely to witness a modest decline in the next decade. But, population growth will keep total consumption increasing, with 13% growth in the next ten years. Over the long run, rice consumption is projected to rise by 35% between 2000 and 2050 (FAO 2006). Consumption growth that is projected in both the medium and long term is lower than what we have experienced in the past decades, but the problem is that the required production growth will have to be met by yield growth rather than the combination of yield and area growth witnessed during the majority of years in the last four decades. The $300 rice price scenario suggests that yield growth in the next ten years will have to be at around 1.5% annually compared with current growth of less than 1% to keep the rice price affordable to the millions of poor in the world, particularly in Asia and Africa. Apart from keeping prices low, the higher yield growth is estimated to expand rice trade flows and improve global rice stocks, which are essential elements for reducing price volatility.

The recent food crisis has further reinforced the urgency of improving productivity growth. But the yield improvements need to be achieved in the face of several 21st-century constraints, including land and water scarcity, environmental degradation, and high input prices and higher incidence of extreme weather. Many ongoing efforts are being made both nationally and internationally to improve productivity by both closing the yield gap and raising the yield ceiling. Greater efforts have been directed toward developing varieties that can grow in unfavorable environments. Several national and international research organizations have been working relentlessly to develop stress-tolerant varieties that can withstand submergence, drought, and salinity.

But, these efforts need to be strengthened further by investing in agricultural research and development to achieve the required yield growth before it is too late as there is a 10–15-year lag between agricultural research spending and its impact on productivity. What we witness now is an outcome of our action toward agriculture in the last two decades in neglecting agricultural research and development support. If we start reinvesting now, the effects are likely to be evident somewhere around 2025. Without any further delay, the world should start reinvesting in agricultural research and use all the tools at its disposal, including agricultural biotechnology, to improve global food security.

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THEME 2:

Organization of rice production and post-harvest operations, and input efficiency

Economic development, land tenure, and the changing optimum farm size

Keijiro Otsuka and Jonna P. Estudillo

Introduction

Owner cultivation is the most common form of organization in agricultural production worldwide (Berry and Cline 1979). In Asia, farming is dominated by peasants who own small landed properties that they operate on a family basis. The Asian system of small owner cultivation is supplemented by tenancy transactions that facilitate land transfers from relatively land-abundant households to households with little land to make the ratio of operational farmland to family labor more equal (Otsuka et al 1992a, Hayami and Otsuka 1993, Otsuka 2007). Among tenancy contracts, share tenancy is much more prevalent than fixed-rent leasehold tenancy.

In China, since the late 1970s, and in Vietnam, since the mid-1980s, collective farms have been transformed into small units of household-operated farms, which are largely similar to owner-cultivated farms in other Asian countries. This agricultural reform has dramatically improved agricultural productivity by enhancing work incentives to farmers (Lin 1988, McMillan et al l989, Pingali and Xuan 1992). As a consequence, small farms dominate throughout Asian countries, with a few exceptions.

It is now a common view in Asia that household farming or owner cultivation is the optimum form of production organization in agriculture. In contrast, tenant cultivation is widely believed to be inefficient because of the adverse effect of tenure insecurity on long-term investments as well as the disincentive effect of output sharing on work effort (Otsuka 2007).[1] Thus, land reform laws in most Asian countries attempt to discourage tenancy transactions, particularly share tenancy, with the expectation that a shift to owner cultivation could result in major productivity gains (Ladejinsky 1977, Herring 1983).

If farm size is small, the farming system is of necessity labor-intensive. This is clearly the case for subsistence farming where major staples, such as rice, are grown. The dominance of small farms does not cause any problem of production efficiency as long as wage rates are low. Indeed, an inverse relationship is found between farm size and productivity, particularly in South Asia, which indicates that large farms are less efficient than small farms, most likely because of the difficulty in supervising wage workers in spatially dispersed and ecologically diverse farming environments. Even in the case of plantation crops, such as sugarcane and pineapples, Hayami (2001) argues that the system of contract farming, in which small farmers produce cash crops and

[1]However, Otsuka et al (1992a) and Otsuka (2007) argue based on the empirical evidence that share tenancy is not as inefficient as generally thought.

deliver to processing plants in accordance with assigned schedules, is more efficient than large-scale plantations, which employ a large number of wage workers.

As the economy develops, however, wage rates increase, so that a labor-intensive small-scale farming system becomes costly. At this stage, farm size must expand so as to introduce labor-saving production methods, such as large mechanization. In other words, the optimum farm size increases with economic development. Farm size expansion may be hindered, however, by land reform regulations, which suppress tenancy transactions to transfer land from small to large farmers. This is likely to be a serious problem in middle- and high-income countries in East Asia, where farm size has traditionally been small and wage rates have been rising sharply. In this chapter, we attempt to shed light on the determinants of optimum farm size based on a literature review, economic theories, and empirical evidence.

We provide a theoretical framework to explain the changing optimum farm size in the second section. We provide an overview of the land tenure systems in Southeast and South Asia in the third section, followed by a review of the literature on the inverse correlation between farm size and productivity in the fourth section. We examine the increasing inefficiency of small farms in Japan in the fifth section, and discuss the implications of the Japanese experience for China, Southeast Asia, and East Asia in the sixth section. We conclude in the seventh section.

A theoretical framework

On the dominance of family farms

Theoretically, it is known that if one of the three markets (land tenancy, land sale, and labor markets) is perfectly competitive, an equally efficient allocation of resources among farming households can be attained in which land-labor ratios are equalized among farms.[2] In the real world, it is unlikely that labor market transaction leads to an efficient resource allocation, because it is generally costly to supervise and enforce hired labor in certain critical tasks in agricultural production. According to the theory of labor employment in agriculture formulated by Feder (1985) and Eswaran and Kotwal (1986), large farmers employ hired labor because of the limited endowment of family labor relative to owned land. Hired wage laborers, however, do not have strong work incentives, as they receive the same wage regardless of how hard they work.[3] Thus, it is not possible to enforce their work effort without explicit supervision. Furthermore, the supervision cost of hired labor probably increases more than proportionally with farm size. Therefore, the high enforcement cost of hired labor will lead to lower production efficiency on large farms, even though those farms would

[2]This is strictly true only if the production function is subject to constant returns to scale (Kevane 1996).

[3]In practice, piece-rate labor contracts, e.g., based on area plowed and amount of products harvested, are more common than daily wage contracts as a piece-rate contract provides more work incentives. A piece-rate contract, however, may induce "quality" shirking, as the quality of work is not considered in the contract.

have the advantage of better access to the credit market owing to the ownership of land that can be used as credit collateral.[4]

The high enforcement cost of hired labor does not imply that casual labor markets are inactive. Since it is easy to observe a work effort or inspect the outcome of work in such simple tasks as weeding, transplanting, and harvesting, daily-wage labor is widely used for these activities. It is costly, however, to employ hired labor for tasks that require care and judgment, such as land preparation, fertilizer application, supervision of a group of hired laborers, and water and pest control in spatially dispersed agricultural environments. Imperfect supervision and labor enforcement in these activities lead to shirking of hired wage labor, which leads to inefficiency of farm operations dependent on hired labor employment. These tasks therefore are usually carried out by family labor on small farms (Hayami and Otsuka 1993).

Even if the labor market fails to function, an efficiency outcome can be achieved, if the land sales market functions well. If the productivity of land is lower on larger farms, there must be an agreeable land price, at which sellers (i.e., large landowners) and buyers (small cultivators) can gain through market transactions. It is well known, however, that the land sales market is inefficient in the real world. This is evident from inactive or almost nonexistent land sales transactions in many places. To our knowledge, Binswanger and Rosenzweig (1986) and Binswanger and Elgin (1988) offer the most plausible explanation for this problem, which takes into account the role of the collateral value of land. They argue that since land can be used as collateral for obtaining credit, the price of land exceeds the present value of future agricultural profits accrued to land by the amount of benefit accrued from the collateral value. Thus, a buyer of land cannot cover the cost of a land purchase solely from future agricultural profits. In order for a land transaction to take place, the buyer must have his or her own funds or additional savings to purchase land. If potential buyers are poor small farmers, they would not possess such extra funds.

Land transactions may also be costly because of imperfect information about the quality of land and inaccurate land registration systems. Added to this is covariate risk in agriculture: many farmers in the same locality commonly want to sell their lands in bad crop years and they want to buy in good crop years, so that land transactions seldom take place (Binswanger and Rosenzweig 1986). When a transaction takes place, it is often a distress sale from poor households to wealthier households at a time of extreme adversity.

A land tenancy transaction is the most common way of adjusting different factor endowments among households. This can be attributed to the relatively less efficient functioning of land sales and labor market transactions than those of the land tenancy market (Skoufias 1995). This does not imply, however, that there is no transaction cost of land tenancy; on the contrary, in a search for contracting partners, negotiations

[4]Feder (1985) and Eswaran and Kotwal (1986) assume that tenancy does not exist, because the landless do not have sufficient access to a credit market to pay for family consumption and purchased inputs and, hence, cannot undertake tenant cultivation. But landlords can and often do provide credit to their tenants, particularly under share tenancy. Therefore, the imperfection of a credit market alone cannot justify the choice of a labor contract over a tenancy contract.

about terms and conditions, their monitoring, and sanctions all require some transaction costs. Thus, there are many self-sufficient owner-cultivator households that neither rent out nor rent in land (Skoufias 1995, Holden et al 2008). As long as the endowment of own land relative to family labor is substantially different among farming households, however, resource allocation in rural economies will be inefficient, unless the land tenancy market functions effectively (Bliss and Stern 1982, Sadoulet et al 2001). In practice in Asia, the majority of famers are family-based owner-cultivators supplemented by a relatively small number of family-based tenant-cultivators.

Changing optimum farm size

When labor is abundant relative to land, labor-intensive methods of cultivation are socially optimum. In such a cultivation system, no major indivisible inputs are used and, hence, there is no major source of scale economies. Roughly speaking, a farm of 1 ha to 2 ha can be managed efficiently by family labor consisting of a few workers, if no machinery is used. Beyond that scale, hired labor must be employed. But then, as was discussed earlier, the monitoring cost rises, which increases more than proportionally with cultivation size. The point is that optimum farm size in low-wage economies would be small because of the intensive use of labor. A substitution of capital for labor is also costly because labor is cheap relative to capital.

As the real wage rate increases, the labor cost increases, particularly if labor-intensive production methods are employed. In order to reduce production cost, labor must be substituted for machinery. In order to operate machinery efficiently, particularly large machinery, farm size must expand. Since large machinery is indivisible, the scale advantage increases.[5] Thus, larger farms are more efficient than smaller farms, so that land must be transferred from the latter to the former. Renting is a practical way to transfer land to the hands of a smaller number of large farms. In fact, landlords are typically small farmers and tenants are large farmers in high-income economies such as the U.S. and European countries.

When farm size is adjusted optimally by land renting as well as land sales transactions over time, we will not observe "scale economies," as all the existing farms are more or less equally large and efficient. Scale economies tend to be observed clearly when small inefficient farms and large efficient farms coexist (Hayami and Kawagoe 1989).[6] This will be observed in the dynamic process of farm size adjustment and also when institutional constraints prevent farm size adjustment. We expect that scale economies will be observed in a high-wage economy in which the government intervenes in land rental transactions and the area control program of farm lands discourages the expansion of rice cultivation areas, so that small farms dominate despite comparatively high wage rates.

[5]The development of a machinery rental market will lessen the scale disadvantages, but the use of large machinery on a number of small farms will be more costly than on a small number of large farms.

[6]In our discussion of scale economies, we follow the conventional use of "farm size" instead of "field size" (Eastwood et al 2009, Otsuka 2007) while recognizing that fields located closer to one another could potentially realize a greater degree of economy of scale.

If a high-wage economy fails to achieve farm size expansion, the comparative advantage in agriculture will be lost and this country will become a major importer of food grains. If many high-performing Asian countries become importers, world grain prices will shoot up and poverty is expected to rise, thereby creating a scenario that is unfavorable to the attainment of the first of the Millennium Development Goals, to eradicate extreme poverty and hunger.

Changes in the organization of production

An increase in optimum farm size accompanies changes in the organization of production. Is a large farm size associated with a lower weight of family labor in total farm labor? Data from different countries in the world compiled by Eastwood et al (2009) show that indeed larger farms tend to employ more hired labor. Hayami (2009) similarly argues that large plantation farms are highly dependent on hired labor in contrast to family farms, which are operated mainly by the farmer's and his or her family members' labor. Family labor is more efficient because family workers have a stronger tendency to follow a conscientious work effort whereas hired laborers tend to shirk in the absence of supervision (Hayami and Otsuka 1993).

It is difficult to predict whether hired labor will comprise a larger share of total farm labor if optimum farm size increases. In North America, for example, the importance of family labor has survived even to more recent years despite the large and growing farm size because of labor-displacing capital and technical progress in mechanization and crop spraying (Eastwood et al 2009). The family labor contribution in rice-farming activities in Central Luzon, Philippines, declined from 1966 to 1994 (Estudillo et al 1999), as the opportunity cost of family labor increased with the increasing availability of nonfarm labor employment opportunities. In rice-growing villages in Central Luzon and Panay Island in the Philippines, the younger generation, which is more educated and has more skills, is found to be more involved in nonfarm activities, in which returns to education are higher than in farming (Takahashi and Otsuka 2009, Estudillo et al 2009).

Indeed, family labor is reallocated in activities where it could be more profitable. In China, Yang (1997) found that the better-educated household members participate in nonfarm wage activities while simultaneously contributing to agricultural management decisions. In Pakistan, Fafchamps and Quisumbing (1999) found that households with better-educated males earn higher off-farm income and divert labor resources away from farm activities toward nonfarm work. In Ghana, labor allocation decisions of farming households are affected by returns to education, which are found to be higher in nonfarm work than in farm work (Jolliffe 1998). In Thailand, Cherdchuchai et al (2009) found that the more educated children of rice-growing households from the Central Plain and Northeast tend to choose nonfarm employment either in rural or nearby urban areas, whereas the less educated children oftentimes migrate to Bangkok and other main cities to participate in casual nonfarm jobs such as construction and domestic work. To what extent the changing optimum farm size and changing labor endowment affect labor allocation decisions of farming households is an issue that remains to be explored in future studies.

An overview of land tenure systems in Southeast and South Asia

In this section, we provide an overview of the agrarian structure in terms of average farm size and inequality of operational landholdings in selected developing countries in Asia (i.e., Bangladesh, India, Indonesia, the Philippines, and Thailand), using agricultural census data from the 1970s, 1990s, and 2000s.[7] Specifically, we would like to examine how average farm size has been changing and whether the dominance of small farms has been strengthened or weakened over time in tropical Asia.

Peasants or small family farms make up a major part of the production organization in Asian agriculture. In fact, the average operational farm size was small, ranging from about 1 ha in Indonesia to 3–4 ha in the Philippines and Thailand in the 1970s (Table 1). In high-performing Southeast Asian countries, such as Indonesia and Thailand, the reduction in farm size has been relatively modest over time partly due to rapid labor absorption in nonfarm sectors and partly due to area expansion. Figure 1 shows that nonfarm wages (represented by a real wage index in manufacturing) have been increasing in these two countries—modestly in Indonesia from 1995 to 2001 and more rapidly in Thailand from 1989 to 2003. The impact of population pressure on farm size dynamism has been mitigated by the rise in nonfarm wages that tends to drive the rural labor force away from the farm to the nonfarm sector.

In contrast, average farm size declined significantly in other economies due partly to rapid population growth in rural areas and partly to stagnant growth of nonfarm sectors. Particularly conspicuous is Bangladesh, where the average farm size declined from 1.4 ha in 1976-77 to 0.6 ha in 1996.[8] In this country, about 50% of farms were smaller than 1.0 ha in 1976-77 and this proportion increased to more than 80% in 1996. Large farms above 10 ha are very few in Bangladesh, suggesting the absence of scale economies.

Although about 50% of farms were smaller than 1.0 ha and their total cultivation area amounted to only 9% of total farmland in India in 1970-71, farms larger than 10 ha accounted for 3.9% of farm households and cultivated as much as 31% of total farmland in the same year. Similarly, in the Philippines, large farms above 10 ha comprised 34% of total farmland in 1971, one year before the initiation of the land reform program that was applied primarily to rice areas characterized by a favorable production environment (Otsuka 1991). There is, therefore, no wonder that the redistributive land reform programs were seriously implemented in these two countries among the five countries examined here. Possibly as a result of land reform implementation, the proportion of large farms and their relative share of operational landholdings declined significantly from the 1970s to 1990s in these two countries. In the Philippines, the decrease in average farm size could be mainly due to population pressure and the implementation of land reform as nonfarm wages grew modestly from 1980 to 1995 (Fig. 1), indicating a less vibrant growth of the rural nonfarm sector than in Indonesia and Thailand.

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[7]Census data for the 2000s for Bangladesh, India, and Indonesia are not available online yet.

[8]Agricultural landless households are excluded from the estimation of average farm size except in India. In Bangladesh, the average size declined to 0.46 ha in 1996 if landless households are considered.

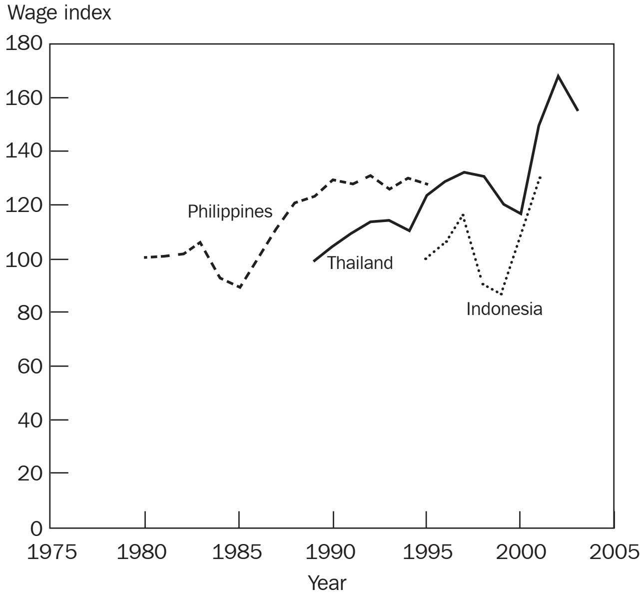

Fig. 1. Real wage index in manufacturing. Deflator is the consumer price index in each country. Source: ILO Key Indicators of the Labor Market online, accessed 17 May 2010, http://kilm.ilo.org/KILMnetBeta/default2.asp.

The Philippines has large agribusiness plantations producing various cash crops using hired labor, which are included among large farms. The available statistics indicate that large farms exceeding 50 ha accounted for only 2.4% of farms but as much as 33.9% of farmland in 1971.[9] Many such farms were plantations. Although large plantations are less prevalent than in the Philippines, they accounted for a major part of large farms in Indonesia. According to Table 1, the importance of large farms above 10 ha declined from 1973 to 1993 in this country. Although the average farm size was relatively large in Thailand, its agrarian structure is characterized by the dominance of small to medium-size family farms. Indeed, large farms greater than 10 ha were relatively few in this country, despite the favorable land endowment.

Although unreported in Table 1, the proportion of tenant households including both pure tenant and owner-cum-tenant households was relatively high in Bangladesh (on the order of 40% to 45%) and the Philippines (30% to 50%) in the 1970s and 1990s, modestly high in Indonesia (about 20%), and low in India (5% to 9%) and Thailand (7% to 15%). In India, in all likelihood, this could be due to the replacement of formal tenancy by informal or concealed tenancy to evade land reform regulations (e.g., Radhakrishnan 1990, Ray 1996, Thorat 1997, Thimmaiah 2001). In Thailand, tenancy is less important than in other countries because there had been uncultivated

[9]The maximum size category in the 1991 agricultural census was 25 ha, so that we cannot compute the share of large farms exceeding 50 ha in that year.

Table 1. Distribution of farms and farmland by operational farm size and the extent of tenancy in selected countries in Asia.

Country	Year of survey	Average operational farm size (ha)	Percentage of farms and farmland[a]			
			Below 1 ha		Above 10 ha	
			Farms	Area	Farms	Area
Bangladesh	1976-77	1.4	49.7	28.8	n.a.[b] (9.4)[c]	n.a.[b] (1.6)[c]
	1996	0.6	80.8	41.1	0.1 (32.4)[c]	1.4 (16.5)[c]
India	1970-71	2.3	50.6	9.0	3.9	30.9
	1990-91	1.6	59.4	15.0	1.7	17.3
	1995-96	1.4	71.1	33.1	1.4	24.1
Indonesia	1973	1.0	70.4	30.0	5.9	10.3
	1993	0.9	70.8	29.8	0.2	3.4
Philippines	1971	3.6	13.6	1.9	4.9	33.9
	1991	2.1	36.6	7.3	2.4	23.3
	2002	2.0	40.1	8.3	2.0	20.5
Thailand	1978	3.7	16.4	2.5	6.0	23.6
	1993	3.4	21.5	3.6	4.5	23.2
	2003	3.1	13.1	n.a.	2.1	n.a.

[a]Since farm size classes differ form country to country, interpolations were made.[b] "n.a." means not available. [c]Farm size above 3 ha.
Sources: (1) Bangladesh, Report on the Agricultural Census of Bangladesh, 1977; 1978 Land Occupancy Survey of Bangladesh; Census of Agriculture 1996. (2) India, National Sample Survey, No. 215, 26th Round, 1971-72; All India Report on Agricultural Census 1970-71; Agricultural Census 1990-91. (3) Indonesia, 1973 Agricultural Census; 1993 Agricultural Census. (4) Philippines, 1971 Census of Agriculture; 1991 Census of Agriculture. (5) Thailand, 1978 Agricultural Census Report; 1993 Agricultural Census.

forest areas that could be opened up for cultivation by poor farmers in this country until recently. Thus, except in this country, cultivated land areas in Asia seem to have been reallocated substantially by tenancy transactions between households.

The proportion of pure tenant households was comparatively low except in the Philippines, implying that the majority of tenants were part owners holding own land rather than the landless. The literature also indicates that the landless households do not have much access to land through land tenancy, particularly in South Asia (e.g., Sharma and Dreze 1996, Sarap 1998). Why this is the case, however, is not clear from the existing studies. One possible explanation is the existence of a minimum size below which the efficiency of farming declines drastically.

Overall, average farm size has been declining in Southeast and South Asia for the last few decades, during which the share of large farms has also been declining. These observations indicate that scale economies in farming are largely absent in tropical Asian countries.

The inverse correlation between farm size and productivity

A large number of empirical studies have been conducted in Asia to analyze the relationship between farm size and yield or value added per unit of area or input use intensity. Although a significant inverse relation is not generally found in Southeast Asia (David and Otsuka 1994), it is found in South Asia, especially in India (Berry and Cline 1979, Dyer 1996-97, Heltberg 1998). The observed inverse correlation is largely explained by differences in land quality and crop mix; large farmers tend to cultivate less fertile land and grow crops of lower output value (Verma and Bromley 1987, Bhalla and Roy 1988, Newell et al 1997).[10] Yet, a significant inverse correlation remains even after controlling for land quality and other differences associated with farm size (Carter 1984, Heltberg 1998). It is often pointed out that the inverse correlation disappeared in India after the Green Revolution because larger farmers applied a larger amount of purchased inputs.[11] According to Newell et al (1997), the inverse relation between farm size and value added per hectare disappeared within a village after the Green Revolution, but the inverse relation between farm size and labor input per hectare remained significant even within a village in India. Ramasamy et al (1994) also obtained similar results from their village study in Tamil Nadu in India. These findings strongly indicate the larger use of family labor and lower use of purchased inputs by smaller farmers, which reflects the advantage of relatively abundant family labor endowment and disadvantage of unfavorable access to credit markets. Heltberg's (1998) careful analysis of household panel data in Pakistan clearly supports our interpretation.

If an inverse relationship exists, the transfer of land from larger farmers to smaller farmers will result in higher production efficiency as well as more equitable distribution of income. The question is why inefficient large farms do not lease out their land to smaller farmers and the landless.

In India, the land reform program applied to tenant-cultivated land with an exemption for owner-cultivated land using hired labor (Khusro 1973, Dantwala and Shah 1971, Appu 1975, Ladejinsky 1977, Herring 1983). Since regulated land rent was set at a level significantly lower than the market rate, landlords were motivated to evict tenants in order to undertake owner cultivation. According to Bhalla (1976), Dantwala and Shah (1971), Ladejinsky (1977), and Bardhan (1989), many landlords actually evicted tenants and converted them to permanent laborers. At the all-India level, the percentage of farm area under tenancy declined from about 20% in the prereform period of the mid-1950s to about 12% in the mid-1960s, at least partly because of the implementation of the land reform program (Narain and Joshi 1969). Thus, large farms employing permanent labor are likely less efficient than small farms based on family labor.

Although the available empirical evidence from India may not be sufficiently conclusive, it seems that India's land reform programs induced tenant eviction and

[10]See also Benjamin (1995) for the case of Java and Barrett et al (2010) for the case of Madagascar.

[11]Empirical evidence, however, is not necessarily strong. See, for example, literature reviews by Dyer (1996-97) and Heltberg (1998).

suppressed the opportunity to rent out the land of large farms.[12] It is also noteworthy that land tenancy is most active in Punjab and Haryana, where the economy has undergone the most dynamic changes in India (Thorat 1997).

In the Philippines, more concrete evidence is available. According to Otsuka (1991), 20% to 50% of tenants were evicted when land reform was implemented in selected villages in Central Luzon and Panay Island. At the same time, a large number of share tenants were converted to leaseholders and amortizing owners and those beneficiaries received significantly higher income than the remaining share tenants (Otsuka et al 1992b). Because of the prohibition of new tenancy and subtenancy, however, land reform beneficiaries, who cultivate large areas relative to the endowment of family labor, began to employ permanent labor (Hayami and Otsuka 1993). Cultivation of large farms by permanent labor, however, is revealed to be significantly inefficient (Otsuka et al 1993). In this way, an inverse correlation was newly created by land reform implementation in rice-growing areas of the Philippines.

In China, where tenancy transaction was discouraged due to the weak tenure security of cultivators, Benjamin and Brandt (2002) found a significant inverse relation between farm size and labor intensity. As in Carter's (1984) study in India, their finding suggests the emergence of inefficiency in resource allocation.[13] This may pose a serious problem in future Chinese agriculture because farmers are actively seeking nonfarm jobs in China (Yao 2000), which requires an efficient reallocation of land among farm households to maintain the productivity of the farm sector (Kimura et al 2010). Using household data, Dong (2000) found from an estimation of the Cobb-Douglas production function that agricultural production is subject to significant diseconomies of scale in China, which suggests an inverse correlation between farm size and productivity.

In sum, evidence is fairly strong that the suppression of land tenancy transactions leads to an inverse correlation between farm size and productivity due primarily to the scale diseconomies associated with difficulty in the supervision of hired labor.

The inefficiency of small farms in Japan[14]

In industrial economies, in which the wage rate is high relative to prices of other factor inputs, extensive mechanization becomes profitable, creating scale advantages and hence enlarging the optimum size of farm operations. Yet, in Japan, the average farm size had remained at around 1 ha or slightly above until the mid-1990s (less than one-tenth of the level in European countries and one-hundredth of that in the United States) despite the remarkable growth in wages. Part of the explanation for

[12]According to Besley and Burgess (2000), who use state-level data on the incidence of poverty, however, tenancy reform, not land redistribution, contributed significantly to the reduction in rural poverty.
[13]Benjamin and Brandt (2002), however, do not observe an inverse relation between farm size and yield. This may well be due to the greater access of larger farmers to cheap credit markets, as in the case of India (Newell et al 1997).
[14]Some parts of this section are drawn from Otsuka (1992, p 100-105).

the dominance of small farms in Japan is likely to lie in the regulation of tenancy transactions by land reform law.

Land reform regulations

Land reform in Japan was carried out from 1946 to l950 under the firm direction of the general headquarters of the U.S. occupation forces (Dore 1958, Ogura 1963). The Land Reform Laws of 1946 authorized the government to purchase all farmlands owned by absentee landlords as well as the landholdings of resident landlords exceeding 1 ha (4 ha in Hokkaido) and to sell them to tenants within two years of the proclamation of the law. Compensation to the landlords was based on 40 times the nominal annual rent in l945 in the case of rice fields and 48 times in the case of upland fields. However, hyperinflation from l945 to l949 reduced the real value of compensation payments to a negligible level.

The government purchased 1.7 million ha of farmland from landlords, which amounted to 80% of the land under tenancy before the land reform, and transferred 1.9 million ha, including state-owned land, to former tenant farmers. As a result, the ratio of farmland under tenancy declined from 45% in 1945 to 9% in 1955. The Agricultural Land Law of 1952 imposed a very low rent ceiling, thereby further reducing the tenanted area ratio to less than 6% in subsequent years. The law also conferred security of tenancy rights, making it impossible for landlords to evict tenants, and set the maximum landholding at 3 ha (12 ha in Hokkaido) to prevent the re-emergence of "landlordism." These reforms significantly contributed to the equalization of income and wealth distribution in rural areas.

Although the regulation of tenancy transactions prevented former landlords from re-accumulating land, it also prevented famers who wished to withdraw from farming from renting out land. As the wage rate increased due to the miraculous growth of the economy from the late 1950s, relaxation of tenancy regulation was urgently needed for farm size expansion, but this was recognized only gradually by the government. The first amendment to the Land Law, in which the 3-ha ceiling on landholding was removed, occurred in 1962. The law was again amended in l970, removing rent control and guaranteeing landlords the return of their lands from tenants upon termination of lease contracts exceeding ten years. In 1980, tenancy contracts for less than ten years were approved on the condition that agreement was reached through the mediation of the village headman. Thus, the tenancy regulation was largely removed, even though the government still set the standard rent, to which the negotiated rent was supposed to conform.

Despite a series of liberalization measures, however, the tenancy market has remained relatively inactive. It is often pointed out that farmers are still reluctant to lease out their lands because they lack confidence that they will be able to get them back. Some of them also fear the possibility of future confiscation of tenanted land.

Farm size and production efficiency

Land reform in Japan did not change the identity of the cultivators of land and, consequently, the distribution of operational landholdings. Average operational farm size and distribution were largely the same in l940 and l960 (Table 2), partly because the land reform did not directly affect the structure of farm size and partly because the land reform regulations restricted its changes (Hayami l988). It is also noteworthy that the average farm size did not change appreciably even from 1960 to l980; it increased from only 1.0 to 1.2 ha, despite continuous and rapid increases in wages and substantial progress in mechanization. There is, however, some indication that the shares of both very small farms (less than 0.5 ha) and relatively large farms (more than 3 ha) increased, particularly by 2005. Such a tendency seems to reflect what Hayami and Kawagoe (1989) call the "polarization" of farm structure in Japan, in which large farmers accumulate land through renting, as well as the purchase of land from small and medium-sized farmers.

The driving force behind this structural change has been the emergence of scale advantages associated with large-scale mechanization. In 1960, there was no appreciable difference in revenue and costs among farms of different sizes categorized into five groups: (1) less than 0.5 ha, (2) between 0.5 and 1 ha, (3) between 1 and 3 ha, (4) larger than 3 ha, and (5) larger than 5 ha. Mechanization in this period was characterized by the widespread adoption of threshers and the introduction of small power tillers. In 1970, however, a significant gap in production costs emerged with the introduction of large machinery; the total cost of rice production per hectare became substantially higher on small farms less than 0.5 ha than on larger ones more than 5 ha, primarily because both labor and machinery costs were much higher on the former. This tendency was further strengthened in 1990—the total cost as well as labor and machinery costs on farms of less than 0.5 ha doubled on farms larger than 5 ha, even though the revenue per hectare remained largely the same across different farm sizes. Thus, the increased share of large farms in recent years is consistent with the emergence of the scale advantage associated with large-scale mechanization. Estima-

Table 2. Percentage distribution of farms by size of cultivated area (ha) in Japan.

Year	Less than 0.5	0.5–1.0	1.0–3.0	3.0–5.0	Larger than 5.0	Average size
1940	33.3	32.8	30.2	2.2	1.4	1.3
1960	38.5	31.7	27.4	1.5	1.0	1.0
1980	41.3	28.1	26.6	2.2	1.5	1.2
2005	22.3	34.4	33.8	5.0	4.5	1.8

Source: Ministry of Agriculture, Forestry, and Fisheries (Japan), Census of Agriculture and Fisheries, various issues.

tion of the translog production function by Kuroda (1987) confirms the emergence of scale economies. Yet, the question remains as to why it is that small farms continue to be so dominant in Japan.

Japanese farmers can be classified into (1) full-time, (2) part-time type I, whose farm income is greater than nonfarm income, and (3) part-time type II, whose farm income is less than nonfarm income. Small farmers are mostly part-time, particularly type II farmers. Many of these people work on their farms on holidays only, while holding regular jobs outside agriculture. Type II part-time farmers accounted for 80–90% of small landholdings of less than 1 ha in 1979 and 1989, and 72% in 2005. Full-time farmers, on the other hand, as well as type I part-time farmers with farm income larger than off-farm income, were larger in terms of farm size in both years. Indeed, full-time farmers are mostly found on large farms.

The increased share of part-time farming may represent an efficient transfer of labor from agriculture to nonagriculture, corresponding to the increasing labor demand in the nonfarm sector during the process of rapid economic growth. Similar patterns are also found in Southeast and South Asian countries where the younger generations of farming households are those who are engaged in nonfarm work (Otsuka et al 2009). But it is obvious that small part-time farmers are less efficient than large full-time farmers because of the emerging scale economies in Japan. We found that the ratio of rented-in land was particularly high among the largest farms of more than 5 ha in 1979.[15] In that year, however, the average ratio of rented-in land was still as low as 5.9% owing to the Agricultural Land Law regulations, which were still largely in effect. Thus, small farmers who wished to withdraw from the farm sector continued to farm but on a part-time capacity, whereas full-time farmers who were willing to expand the scale of their farm operations failed to accumulate land through renting.[16]

When the legal barriers to renting were largely removed in 1980, the ratio of rented-in land increased sharply among farms exceeding 3 and 5 ha, among which it reached 32–33% in l989 and 2005. In contrast, the ratio of land rented out in this year was negatively and strongly associated with farm size. Thus, some farm size adjustments occurred in accordance with the emerging scale advantages.

As was pointed out before, no significant economies of farm size will be observed if the operational sizes of farms are all adjusted to the optimum in order to reap all potential scale advantages. This implies that farm size adjustment in Japan has been too slow to wipe out the disequilibrium manifested in the observed scale advantage. It takes time to adjust farm sizes to optimum levels, so scale advantages continue to exist in a dynamic setting. Further, the memory of land reform, coupled with the imperfect protection of lessors' rights in tenancy transactions, would appear to make farmers cautious with respect to renting out land. This is reflected in the fact that small part-time farmers rent out their lands only to a small circle of relatives and close friends. Such renting arrangements make restoration of equilibrium in land rental markets an

[15]Since renting was uncommon until the late 1970s, data on the ratio of rented area by farm size in early years were not available.
[16]See Hayami (1988) for other reasons for the prevalence of part-time farming in Japan.

impossibility. Herein lies the durable impact of land reform, which is inconsistent with the expansion of farm size to efficient levels in contemporary Japan.

Implications for China and other Asian countries

China

The most important lesson that can be drawn from the Japanese experience is that significant inefficiency in agricultural production arises if farm size remains small in a high-wage economy. If the option of land tenancy is unrestricted, however, tenancy transactions will play an important role in transferring land from inefficient to efficient farm households, thereby contributing to the achievement of higher production efficiency. This view stands in sharp contrast to the common view that tenancy is inefficient.

Following the introduction of the household responsibility system, household farming now prevails in China, which is similar to owner farming in other Asian countries. In China, however, land is collectively owned. Therefore, the land market does not operate freely and, in view of the increasing number of migrants from rural to urban areas, differences in factor endowments are bound to arise. Thus, tenancy transactions must play a role in transferring land from land-abundant to labor-abundant households. Although the Chinese government has strengthened individual land rights (Kung 1995, Yao 2000), it appears that the provision of land rights is insufficient to achieve efficient resource allocation (Kimura et al 2010).

China has been growing rapidly over the last three decades and the wage rate has been rising sharply, particularly since the late 1990s. Although its real gross domestic product (GDP) per capita based on purchasing power parity is still one-fifth of the Japanese level as of 2005, it is comparable to the Japanese level in the 1960s. Given the existing income gap with Japan and other developed countries, the Chinese economy will likely continue to grow rapidly for many years to come based on technology transfer from abroad. Thus, in the longer run, the agricultural wage rate or opportunity cost of family labor will become high, which will induce large mechanization, thereby creating scale advantages. Indeed, the use of riding tractors and combine harvesters has been becoming common in such high-wage areas as Jiangsu and Zhejiang provinces. In these circumstances, the production efficiency of large farms will increase, making it necessary to adjust farm size appropriately through tenancy transactions.

As is reported in Table 3, the import ratio of major grains (i.e., imports divided by the sum of domestic production and imports) has been increasing in China, particularly since the late 1990s. The high ratio of imports of soybeans is explained mainly by the increasing demand for livestock feed. But, potentially also important is the preservation of small farm size, whose average is as small as 0.6 ha, which is becoming less efficient. The production cost of such small farms will certainly increase in the production of all major grains, including rice and wheat, which will lead to an increase in imports of these grains in the future, which will likely result in a sharp rise in world grain prices.

Table 3. Import ratio of major grains, China, 1990-2006.[a]

Year	Rice	Maize	Wheat	Soybeans
1990	0.05	5.30	12.07	15.32
1991	0.12	5.23	12.29	16.77
1992	0.09	5.30	10.27	18.59
1993	0.08	5.03	6.48	14.19
1994	0.43	5.32	7.73	13.24
1995	1.31	9.43	11.03	17.55
1996	0.55	4.79	7.74	22.30
1997	0.23	5.24	2.31	27.66
1998	0.18	3.64	2.32	25.53
1999	0.13	3.67	1.34	31.90
2000	0.20	4.45	2.08	45.22
2001	0.23	4.38	1.88	51.53
2002	0.23	4.00	1.97	45.62
2003	0.29	4.19	1.93	60.11
2004	0.67	3.59	8.36	56.12
2005	0.45	3.45	4.75	63.98
2006	0.58	3.28	1.49	66.42

[a]Import ratio is defined as the ratio of imports to the sum of production and imports.
Source: FAOStat online.

Extremely small farm size presents a major challenge for Chinese agriculture.[17] For example, in order to establish a 10-ha farm, a typical farmer must rent in land from as many as 16 other farmers. If rented fields are scattered, scale advantages potentially arising from large mechanization will not be fully enjoyed. Thus, renting is unlikely to be the major means to create large farms in China. Since 2008, the Chinese government allows the consolidation of village farmlands, which is managed by a small number of selected full-time farmers. In this arrangement, ex-farmers who now work in nonfarm sectors own shares, from which they receive a certain amount of dividends from farming. Whether and to what extent such new arrangements work to create new efficient large farms remains to be seen.

[17] The Chinese recognize that their farm sizes are small to reap economies of scale necessary for domestic production to satisfy domestic demand. The Chinese proposed the construction of new dams and roads in Mozambique and elsewhere in exchange for favorable land leases to run mega-farms and cattle ranches primarily to boost food production to facilitate the rapid export of foodstuffs to China. The most important agenda of this project is to increase rice production, which is destined for the Chinese market since rice accounts for only a small fraction of the Mozambican basic diet. The operation of such mega-farms resembles a plantation system, which is less efficient than family farms because of the high cost of labor supervision or excessive mechanization (Hayami 2009). Furthermore, mega-farms may create social conflict between the capitalist and native people.

What is clear is that unless such drastic measures succeed in enlarging farm size, China, which is a large country, is likely to become a major importer of grains, which would lead to an increase in world prices of grains, including rice. It is difficult to predict whether world rice imports will increase because of inefficiency on small farms in China, because, like Japan, the Chinese government may attempt to achieve self-sufficiency in rice. A large number of countries continue to restrict rice imports and thus only a mere 5% of world rice production is traded in the world market. If small countries continue to restrict rice imports, the production inefficiency of small farms will find its impact on the domestic rice markets of those countries (through a decrease in domestic rice supply and an increase in domestic rice price) without affecting the world rice market.

Southeast Asia

Farms in Southeast Asia are predominantly family farms, which are generally small, consisting of 1–2 ha. Similar to China, Southeast Asia has experienced a decrease in farm size due to population pressure. Many countries in the region have entered the phase of rapid economic growth that has led to increases in wage rates. In rice farming, the major issue is how to enhance the efficiency of family farms by expanding farm size. Thailand's remarkable success of becoming a top exporter of rice lies mainly in the availability of forest lands to expand rice production as well as in improvements in major roads and highways to facilitate rice trade (Hayami 2009). Farm size has been expanding in the Central Plain, where much mechanization has been taking place. Moya and Dawe (2006) reported that Thai farmers are able to save on labor costs in rice production through the adoption of labor-saving combine harvester-threshers.

Although the size of rice farms is small (less than 1 ha in the north and varying from about 0.5 ha to 1.0 ha in the south), Vietnam has successfully ascended to become a major rice exporter. This is attributable to the market liberalization policies (Doi Moi Policy) that are widely believed to be the main factor responsible for enhancing the marketing efficiency and strengthening individual land-use rights and farm management autonomy (Pingali and Xuan 1992). No less important is the introduction of modern rice varieties and the constant improvements of these varieties, thanks to the efforts of regional research centers. Yet, we believe that the small farm size in Vietnam will become a major constraint to maintaining market competitiveness of the rice industry in this country.

The Philippines was the largest importer of rice in 2008 and this is attributed to the high population growth rate that is among the world's highest, limited land suitable to expanding rice production further, and inadequate transportation infrastructure, most important being good-quality roads, which tends to increase the domestic transportation cost and hinders domestic rice trade (Dawe et al 2006). Because of population pressure on the closed land frontier, average farm size in Central Luzon (where the inverse relationship was observed) declined from 2.1 ha in 1966 to 1.9 ha in 2003. Agricultural wages rose only modestly because of a fairly slow phase of development of the nonfarm sector that competes for agricultural labor. Increasing yield through further development of modern varieties and greater intensification of farmland use are the two most important strategies for increasing rice production growth in the Philippines.

South Asia

Bangladesh experienced a decline in farm size, with an average farm holding of 0.6 ha in 1996, which is smaller than that of India, Indonesia, the Philippines, and Thailand (Table 1).[18] According to Hossain et al (2009), the tenancy market expanded rapidly from 1988 to 2004 because of the tendency on the part of large and medium landowners to engage in nonfarm activities and rent out their lands to households whose members previously used to work as agricultural laborers. Although there has been no existing study to our knowledge that explores whether the active tenancy market slows down the decline in farm size, the expanding tenancy market has clearly provided farmland access to land-poor households, which could be an important pathway out of poverty. Although the economy has been growing rapidly, wage rates are not high enough to warrant large mechanization so that small farms remain economically viable.

In India, the inverse relationship appears to be a persistent issue because the country's land reform program has induced tenant eviction and suppressed the opportunity to rent out the land of large farms. Land reform appears to distort resource allocations, as observed in the inverse relationship, and perpetuates the status of the landless agricultural laborers, thereby aggravating rural poverty. Using state-level data, Besley and Burgess (2000) found that tenancy reform, not land redistribution, contributed significantly to poverty reduction.

Concluding remarks

This study attempted to demonstrate that optimum farm size changes as the economy develops and, hence, wage rates increase. In most developing countries in Asia, where wage rates are relatively low, the optimum farm size seems small. Thus, the central land tenure issue is to transfer land from large to small farmers so as to equate the land-labor ratio. If such land transfer is not realized, an inverse correlation between farm size and production efficiency emerges. In all likelihood, the optimum farm size increases sharply as wage rates increase. Then, the critical land tenure issue becomes the transfer of land from small to large farmers to reap the potentially large benefits of scale economies. This institutional innovation, however, may not be induced to take place so as to expand farm size because of the distortion in land markets that was created by government policies.

Judging from the fact that high-wage advanced economies such as the U.S. and European countries are exporters of grains and low-wage economies such as African countries are net importers, high wages clearly do not imply a loss of comparative advantage in agriculture. This is because labor can be substituted for by capital as well as land, which is less expensive than labor. Such substitution is possible only when farm size becomes sufficiently large.

[18] Hossain et al (2009, Table 5.1, p 97) reported that the average farm size in a nationally representative survey in Bangladesh was 0.59 ha in 2004.

Asian countries are handicapped in farm size expansion because of the small endowment of land relative to labor. This would imply that, as the wage rate increases, these countries are likely to lose their comparative advantage in agriculture. The extent of losing the comparative advantage, however, will depend on the pace of farm size expansion. If farm size does not expand sufficiently fast, as in the case of Japan, the comparative advantage in agriculture will be lost and that country will become a major importer of grains. If a large country like China fails to expand farm size rapidly, the world may experience food shortages as large food imports are likely to affect grain prices in the world market.

Finally, inasmuch as many parts of contemporary Africa have started to move toward the Asian regime of land scarcity and labor abundance faced with increasing commercialization of agricultural products, African farms will likely experience a disequilibrium in the land-labor ratio. The landless agricultural class is bound to emerge, tenancy arrangements will inevitably evolve, and land rights will be increasingly individualized. An important lesson for Africa is to minimize excessive government intervention in the land market in order to avoid getting into the inverse correlation trap that was experienced in India and the Philippines. Government efforts should focus on establishing well-defined property rights, which is a crucial element in the efficient working of the rural land market.

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Rice seed provision and the evolution of seed markets

Robert Tripp, Ruifa Hu, and Suresh Pal

Introduction

When *The Rice Economy of Asia* was published in the mid-1980s (Barker et al 1985), it was hardly necessary to consider the subject of rice seed production and delivery. At that time, most rice seed in developing countries was provided by public-sector programs and alternative strategies were hardly in evidence. The fact that this volume includes a chapter on seed provision is an indication of the changes in policy, technology, and markets that have taken place during the past few decades and acknowledges the resultant diversification of national seed systems. Many of the traditional public rice seed provision strategies are now challenged, on the one side by declining political support and their increasing budgetary burden and on the other side by a thriving private seed sector, bolstered in part by the advent of hybrid rice and proprietary technologies such as transgenics. Whether farmers, who have not always been adequately served by public seed provision, will find that the new options are more responsive to their needs remains to be seen. But it is important to understand the forces behind the significant evolution in rice seed provision that is taking place.

This chapter will examine the nature of the changes in rice seed systems.[1] It begins with a brief review of the rice seed systems that have been in place until recently. Next, it discusses the factors that have challenged the public seed provision model and describes some of the innovations that have occurred in seed provision for inbred rice varieties. It then examines the case of hybrid rice seed provision. The chapter concludes with a brief consideration of issues for the future.

Rice seed systems and the Green Revolution

Farmers have saved, selected, and traded seed since the beginning of agriculture, but there have also been numerous instances of government intervention in seed provision. The 11th-century Song dynasty imported seed of early-maturing, drought-tolerant rice varieties from Vietnam to China and oversaw its distribution to farmers (Bray 1986). In late 19th-century Japan, fertilizer-responsive rice varieties, originally developed by farmers, were tested and diffused through state-organized farmer groups and seed

[1]The chapter will use the term rice seed rather than paddy seed (frequently used to indicate that the planted seed includes the grain encased in the hull). The chapter also distinguishes between seed of conventional inbred rice varieties (produced by multiplying seed of the previous harvest) and hybrid rice seed (the product of crossing two or more inbred lines).

exchange societies (Francks 1984). In the mid-20th century, national governments in Asia were responsible for various efforts to distribute seed, particularly of new varieties, but in most cases major strategies for formal rice seed production and delivery did not emerge until the Green Revolution was well established in the 1970s. The development of short-straw, fertilizer-responsive rice and wheat varieties transformed many Asian farming systems and led to an increased demand for seed. National governments had to develop significant seed provision capacity.

Public seed companies were established in some countries. In India, the National Seed Corporation was established in 1963, and in the mid-1970s World Bank projects helped establish 13 state seed corporations, which eventually provided the majority of the country's commercial seed. Similarly, Pakistan established two provincial seed corporations in Punjab and Sindh that sold seed through parastatal input suppliers. The Bangladesh Agricultural Development Corporation (BADC) was established in 1976 to multiply and sell seed, building on the experience and infrastructure of several earlier public input supply mechanisms.

Other countries developed a range of strategies for public rice seed provision. In China, each prefecture had a seed company that produced mostly foundation seed that was provided to county seed companies that contracted farmers to produce commercial seed that was sold at government outlets, usually township agricultural extension agencies. In Sri Lanka, most rice seed in the 1970s and '80s was produced by contract farmers or government farms under the supervision of the Department of Agriculture and sold through government-organized cooperatives. Both Thailand and the Philippines established systems in which foundation seed produced by a public research institute was provided to a decentralized network of seed producers for multiplication to certified seed, which was usually supplied to farmers through extension programs.

During the 1970s and '80s, government seed interventions were also common elsewhere in the world. In Colombia, a large public seed corporation was part of the state agrarian bank, although rice seed was produced with the facilities of the rice producers' federation (FEDEARROZ). In Egypt, the government Central Administration for Seeds contracted farmers to produce certified seed, which was sold through agricultural cooperatives. In several West African countries, government programs or development projects produced seed as a way of encouraging rice production.

There are several justifications for this heavy government involvement in rice seed provision. All of the seed was of varieties bred by public agricultural research institutes. Seed supply was only one part of concerted government efforts to promote Green Revolution technology; fertilizer and other inputs were often managed by the public sector and input subsidies were common. These efforts were part of major government strategies to achieve food security. Although farmers were eager to obtain seed of new varieties, their seed-saving practices meant that there was relatively little sustained demand; once the seed was acquired, farmers had little incentive to purchase fresh supplies. The private sector was not attracted to an uncertain market for a bulky commodity with low profit margins, particularly in the face of frequent government subsidies. In addition, many government policies discouraged or prohibited private-sector participation in seed markets for basic staples.

Although most of these public rice seed systems provided only 5% to 15% of the rice seed used in any season (the rest being farm-saved or informally accessed seed), the quantities of seed supplied were significant and they helped promote the use of many new and productive rice varieties. These large public seed systems were less than perfect; there were often complaints about seed quality, and matching seed supply to farmers' variety preferences was not always achieved. But, as long as the governments were committed to supporting agricultural input supply, public funds were available for sustaining formal rice seed systems. It was not until budgetary and policy pressures began to appear that some of the monolithic state seed systems began to be challenged by alternative seed provision strategies.

The changing scenario post-Green Revolution

The pressures for change

The status of public rice seed provision in a number of countries began to encounter challenges in the 1980s. In some cases, this was related to a shift in government priorities and a lessening of the emphasis given to Green Revolution campaigns. Because many of these public programs included direct or indirect subsidies, budgetary implications were important, especially under pressures for structural adjustment. At the same time, policy shifts in some countries allowed greater leeway for the private seed sector, and the availability of hybrid technology for several other crop staples (and eventually for rice) meant that the incentives for private-sector participation were increased. In the 1990s, the widespread enactment of plant variety protection (PVP) legislation and the advent of transgenic and other proprietary technology brought further incentives for private investment. In addition, the fact that the large public seed provision systems tended to focus on better environments, contributing to a widening gap between farmers in favored and marginal environments (which was unlikely to be addressed by private-sector seed companies), led to a range of new public and NGO initiatives for variety testing and seed provision in less favored environments.

In some cases, public rice seed systems remained dominant. In the Philippines, foundation seed of public rice varieties is produced by the Philippine Rice Research Institute (PhilRice), the national rice research institute. This foundation seed is then provided to members of the National Rice Seed Production Network (SeedNet), whose members include state universities and colleges, regional integrated agricultural research centers of the Department of Agriculture (DA), Regional Field Units, cooperatives, and seed growers. Network members are responsible for producing registered seed, which is used for the production of certified seed by accredited seed growers and selling it at government-controlled prices, either from their own outlets or through DA programs. In Thailand, foundation seed of rice varieties is produced by the public Rice Research Institute and multiplied by contract growers associated with Rice Department seed centers that have seed conditioning capacity; the seed is then sold to farmers through various outlets, including extension, cooperatives, and community seed centers.

But even where public rice seed provision systems were maintained, changes in policies, regulations, and technology had important implications for the way that rice seed was delivered. The extent and direction of change varied significantly across countries. Many countries witnessed various levels of private-sector participation, and some also began to invest more in community-level activities for seed production and distribution. Thus, a combination of factors related to government budgets, the emergence of the private seed sector, and concerns for equitable agricultural development led to a diversification of rice seed provision mechanisms in many countries. The rest of this section summarizes some of the major outcomes. It looks at changes in the regulatory environment, describes some examples of the emerging private sector for inbred rice seed, reviews the implications of the proprietary technology for the rice seed sector, and describes some of the programs that have addressed rice seed provision for marginal environments.

The regulatory environment

The diversification of rice seed systems is partly dependent on policies that allow private-sector participation, but it is also related to changes in laws and regulations, both those that accommodate private seed provision (such as modifications in seed certification and quality control) and those that provide additional incentives for private seed businesses (particularly methods of intellectual property protection).

Formal seed systems have always attracted regulatory attention because seed is a product with qualities (e.g., variety identity, viability) that are not always immediately apparent to the buyer. The principal response has been to establish seed certification capacity. Strictly speaking, certification refers only to the process of verifying the genetic identity of the variety. In most cases, however, the regulatory agency also includes the control of physical seed quality (germination, purity, etc.) and the term certified seed usually refers to both variety identity and physical quality.

Most public rice seed systems have included mandatory certification. Even though certification was often the responsibility of an independent government agency, as long as there was a public monopoly for seed production, the regulator had only a single “client.” The management of seed certification in these circumstances is relatively straightforward, but, as formal seed systems diversify, the status of seed certification becomes more complex. For instance, should certification be mandatory for all producers, or is it possible to rely more on commercial reputation to ensure quality? And, regardless of its status, should certification be supported by public budgets or insist on full cost recovery? The answers to these questions have varied across countries, and an additional complication is the considerable distance that often exists between formal regulations, on the one hand, and the resources to enforce them, on the other. In general, there has been a trend away from mandatory seed certification in response to a growing private sector and/or in recognition of the fact that government resources are inadequate to manage a comprehensive certification scheme involving widely dispersed seed producers. In India, state seed certification agencies are still in place and the majority of rice seed from state seed enterprises is certified, but seed may also be sold as "truthfully labeled" (TLS), for which there is no third-party monitoring of the seed production process but the producer is responsible for ensuring minimum standards for germination and purity and is liable to penalties if these are not met. A number of other countries allow rice seed to be sold as TLS, such as Bangladesh, Pakistan, and Nepal (where it is called "improved seed"), or recognize seed classes that require less rigorous inspection than certified seed. In some countries (such as the Philippines), the government provides a subsidy for certified seed to encourage its use.

Variety registration is another element of seed regulation that deserves attention. At the time of the Green Revolution, virtually all varieties of staple crops were the products of public plant breeding and all countries had procedures for testing new varieties for "value in cultivation and use" (VCU) and registering them for release. With the growth of private plant breeding, the question of variety release requirements has become more complex. Although most developing countries still require that any new variety of a staple pass some type of performance test, there are instances of flexibility. Until recently, India did not require varieties developed by the domestic private sector to pass performance tests, but the Seed Bill of 2004 (which is still being debated) reverses that and would require that all varieties, public or private, be submitted for some type of performance testing. China requires variety release trials for many crops (including rice), usually managed at the regional or provincial level.

A relatively recent seed regulatory issue for developing countries is PVP. All countries that are members of the World Trade Organization (WTO) are required to establish some form of intellectual property rights (IPRs) for plant varieties (patents or PVP); the least developed countries have until 2013 to develop the requisite legislation. PVP provides the plant breeder (public or private) with the capacity to determine who can produce seed of a variety, and under what conditions. One of the most controversial areas of PVP is that of farmers' privilege, the right to save seed from the previous harvest for planting the next season. The most recent (1991) convention of UPOV (International Union for the Protection of New Varieties of Plants) allows breeders to deny farmers the right to save seed of their variety, but it is interesting to note that most Asian countries that have already established PVP systems have chosen not to join UPOV 1991, in part to defend the farmers' privilege (e.g., Kanniah 2005); Vietnam is an exception to this rule. The inability to keep farmers from re-using seed of a variety (or indeed the difficulty in enforcing any law restricting seed saving) is a major disincentive to private investment for inbred rice varieties. Hybrid rice seed, on the other hand, needs to be purchased each season and the inbreds serve as trade secrets, so there is much more private interest in hybrid rice.

The advent of biotechnology has greatly increased the complexity of intellectual property rights (IPR) in agriculture. Farmers' access to varieties can be controlled in several ways. A few countries (such as the U.S.) allow plant variety patents, which not only prohibit seed saving but also deny access to the variety for other breeders. Even without a PVP law, a company can market seed with a grower agreement that prohibits seed saving. A country may also decide to curtail farmers' privilege for transgenic varieties. The genes, processes, and tools used in genetic transformation are all subject to national patent laws, creating a tangled web of restrictions for anyone producing and marketing transgenic varieties.

The private seed sector

The private seed sector has become an important factor for rice in many countries. In some cases, the public seed enterprises remain in place, while in others they have diminished in size or disappeared. Seed demand needs to be sufficiently high to warrant private investment. Although most rice seed is farm-saved, even a relatively small proportion of farmers who buy from the formal market in any one season may represent adequate demand, as long as they are fairly concentrated and accessible to input markets and their variety demands are not too diverse or variable. The relative scope for the private seed sector also depends on the extent to which government policy provides a level playing field. Most of the private activity for seed of inbred rice varieties in Asia involves firms producing and delivering seed of public varieties. Plant breeding is still largely in the hands of public research but private seed companies play an increasingly important role in multiplying the seed and bringing it to market.

One of the first instances of a move toward private-sector rice seed production was in India. National seed policy experienced significant shifts in the 1980s, making it easier for private seed companies (which had largely been confined to horticultural crops) to enter the market for field crops. Although much of the initial commercial activity was in hybrids (sorghum, pearl millet, maize), the infrastructure that was developed was available for expansion into inbred varieties of rice. Virtually all of the inbred rice varieties sold by private Indian seed companies are developed by public institutes (particularly state universities). The public institutes sell breeder seed of their varieties to public seed enterprises and private firms. The companies use the breeder seed to produce foundation seed and commercial seed, using contract growers. A study in 1998 in Andhra Pradesh found that more than 40% of purchased rice seed was provided by the private sector, including some of India's largest seed companies, many small firms (some of which relied on other companies for foundation seed), and a number of cooperatives (Pal et al 2000). Data from 2002 indicate that 80% of commercial rice seed in Andhra Pradesh and 60% in Haryana come from private seed providers (Singh et al 2008).

The extent of the private rice seed market in India varies by state and, because statistics on private seed sale are not available, estimates are possible only in states where specific studies have been done. Those states with highly commercial rice markets, where farmers are more likely to value the convenience and quality of purchased seed, are more likely to attract private seed enterprises that compete with the public seed producers. A survey in one district of Haryana found that farmers obtained 60% of their rice seed from commercial (private or public) sources (Singh et al 2008). Nationwide data show that about 25% of rice seed is purchased on the formal market (certified or truthfully labeled) each year, and the supply of formal-sector rice seed rose from about 150,000 tons in 1991 to about 420,000 tons in 2006.

China has also witnessed a significant change in its seed policies, beginning with a new seed law in 2000. Most of the county seed companies (which were the backbone of the public seed provision system) have disappeared and about 7,000 private commercial seed enterprises have emerged. Plant breeding has also been placed on a more commercial basis. Although a few private seed companies invest in their own breeding programs for inbred rice varieties, the majority of these varieties are still the products of government research institutes. Although there are still some public seed companies, many public rice varieties are either licensed to independent private firms or sold by seed companies connected to the research institutes. The widespread use of PVP has contributed to the success of these strategies and some provincial governments help pay the costs of PVP application as an incentive for technology development. On the other hand, there are cases (e.g., Guangdong) where the provincial government subsidizes breeding institutes' budgets according to the area sown in their varieties, promoting strategies that favor wide diffusion of public varieties by any means rather than licensed access to designated seed producers.

The government of Pakistan established a new policy in 1994 that allowed the participation of private companies in the market for field crop seed. This resulted in a rapid growth of private seed firms; well over 200 companies are registered to produce rice seed and the private sector accounts for approximately 75% of the rice seed marketed in Pakistan. In Bangladesh, the Seed Act of 1998 loosened restrictions on the production and certification of foundation and commercial seed, so the private sector and NGOs could participate. Private seed companies began to produce and market rice seed, although they found the competition from public and large NGO programs a disincentive (Hossain et al 2001). The state BADC continues to produce the majority of seed of inbred varieties sold in the country. In Nepal, rice seed is currently provided through three channels: nearly half is produced by a small number of private seed companies, about a third is provided at the district level by a decentralized Department of Agriculture program, and the rest is produced by the public National Seed Corporation. In Sri Lanka, a large agribusiness firm leased some of the government seed production facilities and began to provide a significant amount of rice seed; they were apparently able to provide more efficient management of seed production facilities than the government (Mahrouf et al 2004). In Indonesia, changes in seed policy have shifted rice seed production away from the public sector, and the majority of inbred rice seed is produced and sold by private firms.[2]

In the Americas, where much rice is grown on large farms, private rice seed provision is the norm, often supported by rice grower associations. In the U.S., most rice seed of public varieties has been produced and sold by small seed companies, which are often simply rice farmers with seed-conditioning equipment and links to the public agricultural universities through rice producer associations. Similarly, much of

[2] The movement away from a single state supplier toward a range of public, private, and NGO seed providers, as well as the fact that centralized seed certification is often no longer mandatory, means that accurate statistics on total rice seed sales (and breakdowns by category of supplier) are difficult or impossible to obtain for many countries. Thus, the discussion of seed system diversification in this section is, unfortunately, not accompanied by cross-country statistical comparisons.

the commercial rice seed in Rio Grande do Sul, Brazil's major rice-producing state, is of varieties developed by the state rice research institute, Instituto Rio Grandense do Arroz (IRGA), which organizes and supports selected farmers as seed producers and sellers. The system includes state-funded supervision and oversight, but the sale of seed is a profitable enterprise for the participating farmers. Rice grower associations in several other Latin American countries follow the same strategy of depending on selected farmers as seed producers and sellers. In Colombia, public rice seed provision has been completely replaced by the activities of private seed companies and the cooperative FEDEARROZ.

Private seed companies are still the exception in most of sub-Saharan Africa, but the promotion of new rice varieties, particularly the NERICAs ("New Rice for Africa"), has led to some private production and sale of rice seed in Uganda, for instance.

Proprietary technology and private rice breeding

Most private-sector rice breeding is related to hybrids, but there are a few examples of private breeding investments in rice inbreds. Colombia has several small seed companies that produce and market their own proprietary rice varieties. This is encouraged by Colombia's rather strict seed certification regulations and limitations on seed saving, as well as by a well-enforced PVP law. These companies also benefit from the fact that most of the rice is grown by large commercial farmers who are frequent seed purchasers. A few companies in India have tried to develop and market their own inbred rice varieties, but with little commercial success to date.

A factor that could affect the public-private balance for inbred rice breeding is the possibility of transgenics. A number of transgenic rice varieties have been developed (for disease or insect resistance, as well as "Golden Rice" with high pro-vitamin A content), but none have yet been released for commercial use. In countries with advanced public research capacity, such as China and India, transgenic varieties may be developed by public institutes and the seed could be marketed through the same (increasingly private) channels as seed of conventional rice varieties. Elsewhere, it is more likely that proprietary transgenes would have to be licensed for use in public inbred varieties. In either case, concerns about biosafety and the stewardship of transgenic varieties would have to address the inevitability of seed saving and informal seed diffusion for transgenic inbred rice varieties in most developing countries. It remains to be seen if the possibility of incorporating transgenes in rice varieties encourages the private sector to compete with public inbred rice breeding. The increasing availability of IPR instruments for plant varieties combined with the promise of transgenic technology makes it more likely that multinational corporations (MNCs) could capture an increasing proportion of the rice seed market. Srinivasan (2003) has shown how national seed industries for major crops have grown increasingly concentrated in recent years.

In many cases, biotechnology firms may simply prefer to license their technology for use in rice inbreds. The example of nontransgenic herbicide-tolerant rice technology may provide some lessons on what arrangements could emerge when proprietary traits are incorporated in inbred varieties. “Clearfield” is a proprietary trait from BASF based on a mutation (not a transgene) that provides resistance to certain herbicides. It is particularly useful for controlling the weed red rice, which is a serious problem in North and South America. A number of “Clearfield” inbred rice varieties are currently available to farmers in the U.S. These are based on public rice varieties that incorporate the licensed herbicide-resistance gene. The seed is produced and sold in the same way as conventional varieties (except that an intermediary organization handles stewardship and IPR issues). Argentina and Brazil have similar “Clearfield” conversions of public rice varieties. These arrangements (for inbred varieties) are more likely to emerge where PVP or other types of intellectual property protection can be enforced to limit seed saving, or the nature of the variety discourages farmers from re-using the seed.

Seed provision innovations for marginal environments

The past several decades have also seen the development of several other types of rice seed programs. Many of these are based on strategies that encourage farmer seed production. They respond to inefficiencies in large government seed schemes and their inability to address location-specific variety demands. These programs typically provide foundation seed, training in seed production methods, and some supervision to selected farmers. Occasionally, the state seed certification service monitors seed quality, but more often other arrangements are made, such as deputing local extension agents to help assess seed quality or marketing TLS.

Once the seed is produced, there are several options. In many cases, the organizing government department, development project, or NGO collects the seed, conditions and bags it, and then sells or provides it to farmers. In this case, the agency is similar to a seed company (except that seed price and sales outlets may not be commercial) and the participating farmers are the equivalent of contract seed growers. Several large NGOs in Bangladesh follow this strategy, and in some cases their scale and commercial orientation make them difficult to distinguish from conventional seed companies (Bashar et al 2005). In other cases, once the farmers produce the seed, they are encouraged to sell it locally, from their homes (Van Mele 2005). In Nepal, the District Seed Self-Sufficiency Program (DISSPRO) operates in about 60 districts; it organizes farmer groups, provides training and “certification,” and facilitates access to foundation seed.

Attention to the promotion of specific varieties may also lead to local seed production initiatives. Increasing interest in participatory variety selection (PVS), in which farmers collaborate with breeders to test and select promising lines and develop varieties well adapted to local conditions, has also led to the organization of local seed production of new varieties (e.g., Virk et al 2003). Donor efforts to promote NERICA rice varieties in several West African countries with poorly developed formal seed systems have also relied on a strategy of organizing community-level seed production and distribution.

The small-scale rice seed production projects in Asia and Africa sometimes have aspirations of achieving economic viability, believing that the temporary schemes will "graduate" to become permanent rural enterprises, providing seed at commercially remunerative prices. This is generally problematic and the track record to date gives little reason for optimism (Tripp 2001). Although local-level, informal seed production and distribution can be an effective way to introduce new varieties or address temporary local shortages, the step up to becoming a formal commercial enterprise is full of challenges. Besides deciding how to direct and manage an enterprise shared among many resource-poor participants, the transaction costs that are usually paid by the seed project (acquiring foundation seed, ensuring quality control, promotion, marketing) must be addressed by the new enterprise. The profitability of relying on demand from a small, local area is tenuous, and the argument that such activities are needed in marginal areas where farmers chronically run short of seed must consider the wisdom of organizing seed production in risk-prone areas.

Even if most of the small-scale rice seed production projects are commercially unsustainable, they attempt to address real challenges for which there are no easy answers. Neither large public programs nor conventional commercial seed companies will likely be able to serve the needs of farmers in more isolated areas, whose demand for seed may be particularly dependent on climatic risks and specific variety requirements. Often farmers in marginal environments grow a wide range of cultivars; a study in a village in Orissa found farmers growing a total of 33 local rice varieties and 11 modern varieties (Kshirsagar and Pandey 1996). Similarly, a village in Sierra Leone was found growing 49 different rice varieties (Richards 1986). The argument for public or charitable support to improve seed supply in these environments is often justifiable, as long as unrealistic expectations about the commercial viability of small-scale seed schemes do not divert attention from thinking about the most efficient combination of public and private resources required to support farmers in more marginal or isolated areas.

It is also important to recognize that indigenous farmer-to-farmer seed diffusion is often quite effective for introducing new varieties. There are many instances where farmers' local seed testing and acquisition patterns have been responsible for the wide-scale uptake of a new variety. In the late 1960s, a rice variety (Mahsuri) was rejected in All-India Coordinated variety trials, but farmers who had seen the trials were impressed with its performance, acquired and grew some of the seed, and passed it on to their neighbors. By the 1980s, it was the third most widely grown rice variety in India (Maurya 1989). Similarly, a Ghanaian farmer brought 0.5 kg of seed of a rice variety grown across the border in Côte d'Ivoire to test in his field in 1987; within a few years, the variety had diffused, mostly through seed purchases among fellow farmers, to account for more than 60% of rice planted in an area of western Ghana (Marfo et al 2008).

If farmers don't have access to a commercial seed market or their resources do not permit the frequent purchase of fresh seed, there are ways of improving farm-level seed management to address impurities, seed-borne disease, weed seed, or storage problems. The challenges are considerable in devising improved seed management techniques that are adapted to small-farm conditions and resources, but recent experience in Bangladesh with new extension methods that address the entire farm family (Harun-Ar-Rashid 2005) and farmer field schools for seed production in Vietnam (Tin et al 2008) have claimed to show promising results.

The hybrid rice seed market

The most significant recent development for the rice seed industry has been the emergence of hybrid rice technology. Hybrid seed is the product of a cross between two inbred parents; the progeny is more productive than either parent (the phenomenon of hybrid vigor) but this advantage is lost, or diminishes significantly, in the second generation. Thus, farmers should buy fresh hybrid seed each year. Besides contributing to increased yields, hybrid technology is a boon to the seed industry, significantly raising demand for seed. The spread of hybrid maize in the U.S. in the 1930s was a remarkable example of rapid technology adoption (Griliches 1957) that stimulated the growth of the private seed industry for field crops. Similarly, the emergence of private companies in India selling hybrid seed of sorghum and pearl millet in the 1980s was one of the key elements in the subsequent growth and diversification of the Indian seed industry (Pray et al 1991).

Inbred crops such as rice have usually been more of a challenge for hybrid development, but Chinese research led to the world's first commercial release of hybrid rice in the mid-1970s, and by 1990 at least half of China's rice area was planted to hybrid seed. Despite the technical achievements represented by hybrid rice, its exact place in Asian and other rice systems has yet to be determined. Its yield advantages are important, but the hybrids require adequate management, and current hybrids are suitable only for irrigated environments. The costs of producing hybrid seed are significantly greater than those for inbred rice seed and, although the seeding rate for hybrid rice is much less than for inbred varieties, the cost of seeding 1 ha is considerably higher than that of conventional seed.

The high seed cost is due to the requirements of seed production. Most current hybrid rice seed is produced in a "three-line" system. This is based on a cytoplasmic male sterile (CMS) line which first must be crossed with a "maintainer" line to produce seed of the female parent. This is then crossed with a "restorer" line, or pollen parent, to produce commercial hybrid seed. The process is fraught with challenges. The numbers of adequate CMS, maintainer, and restorer lines are limited, and their performance is often affected by environment. The parent lines must be exceptionally pure. The timing of planting of the parent lines (and use of growth regulators) must be carefully planned to synchronize fertilization. Planting ratios, physical and chemical treatments of the parent plants, and aids to pollen flow (such as shaking the plants with a rope or stick) must all be available to ensure adequate pollination; and exceptionally thorough roguing and harvest techniques must be practiced. These requirements imply unusually high seed production costs (and the need for providing contract seed growers with the requisite technical skills), and seed yields are quite low.

More recently, the Chinese have begun to employ two-line hybrid rice seed production methods. These are based on photoperiod-sensitive or thermosensitive male sterility, which means that seed of female lines may be produced normally, under appropriate environmental conditions, rather than crossing with a maintainer line. This system saves one set of crosses, but requires access to a range of environments and very careful management. It also allows a much wider range of parents to be used. It remains to be seen how generally applicable this system is, and the extent to which it reduces seed production costs. Other innovations are surely in the pipeline, but reducing the costs of hybrid rice seed production remains one of the great challenges for the technology.

China maintains the lead in hybrid rice and Chinese farmers were using approximately 600 different rice hybrids in 2007, accounting for about 53% of national rice area. Although the majority of the hybrid varieties in use have been developed by public institutes, they are all sold by private seed companies. In about two-thirds of the cases, the hybrids are developed and protected by public institutes, but they are licensed to private companies for multiplication and sale. In other instances, a public hybrid is assigned exclusively to a private seed company that has responsibility for obtaining PVP for that variety. Finally, about 10% of the rice hybrids developed in China are the products of private plant breeding. Some of the larger seed companies are actively engaged in export markets for hybrid rice seed. Previously, it was common for Chinese hybrid seed to be produced abroad, and Chinese seed company technicians often worked in the second country and supervised production with a local partner company. However, the policy has recently changed and most hybrid rice seed for use in other countries is now produced in China.

India has also invested heavily in hybrid rice. Early hybrid varieties had trouble gaining acceptance because of low grain quality, but recent releases have included attention to better quality as well as earlier maturity. Hybrid rice is currently planted on more than a million hectares in India (about 3% of total rice area). Some hybrid adoption has even taken place in rainfed areas of eastern India that were not originally targeted for hybrids. Most of the major public rice breeding programs work on hybrids. Research organizations usually enter into contractual agreements with private seed companies to produce and market public hybrids on a nonexclusive basis. The seed companies either purchase breeder seed from the public research organization or pay a royalty; in either case, the research organization receives approximately 3–4% of the seed price. These arrangements are facilitated by the recently implemented PVP law in India. The quality of the foundation seed used in hybrid production is crucial and public organizations do not always have the facilities or incentives to devote attention to this area. The Indian Council of Agricultural Research (ICAR) has recently established a directorate of seed research, which has provided more support to source seed production for public hybrids. In addition, a nonprofit foundation (Indian Foundation Seeds and Services Association) has established a facility for foundation seed multiplication as an intermediary for private or public seed producers.

The private sector is also active in hybrid rice breeding in India, including both domestic firms and MNCs. About two dozen public and private rice hybrids are available in India, but only a few (public and private) hybrids dominate the market. India also exports a small amount of hybrid rice seed to Bangladesh, Vietnam, and the Philippines. Because private breeding plays a prominent role in rice hybrids (and private seed companies produce about 90% of all hybrid rice seed), there is some concern that the government may try to place limitations on the price of private hybrid rice seed, a policy instituted for transgenic (*Bt*) cotton seed (Sadashivappa and Qaim 2009).

Hybrid rice has drawn considerable attention elsewhere in Asia, although the interest varies considerably between countries. Hybrid rice accounted for only about 3% of Asia's rice area (outside of China) in 2008 (Pandey and Bhandari 2009). The Bangladesh government has a policy of promoting hybrids, particularly for boro (the irrigated dry season). A public-sector hybrid (from the Bangladesh Rice Research Institute) is currently produced and marketed by BADC. The Bangledesh Rural Advancement Committee (BRAC), a very large NGO that has established its own plant breeding and seed production capacity, has developed and markets its own rice hybrid. But, the majority of hybrid rice seed currently marketed in Bangladesh consists of foreign varieties. Hybrids are also promoted in Indonesia, which has public rice hybrids (produced and sold by private companies) but also imports hybrid seed and produces licensed foreign hybrids within the country. In the Philippines, public rice hybrids (produced and marketed through a public network) compete with imported hybrids. A number of national governments try to promote the use of rice hybrids through subsidies on seed and other inputs, a policy that has often attracted considerable criticism (e.g., Cororaton and Corong 2009).

In addition to the activity of the Chinese and Indian private sector, hybrid rice has attracted a number of MNCs, including Bayer, Pioneer (Dupont), and Syngenta, that are already marketing hybrid varieties in Asia, and some MNCs are also targeting Latin America. The extent to which this interest is based on the hybrids themselves or is more directed to the hybrids' potential for delivering transgenic traits is not clear.

Hybrid seed increases seeding costs and requires good crop management, so it is not appropriate for all environments. Many of the varieties available to date receive somewhat lower prices in the market because of less acceptable grain quality, which means that their yield advantage must compensate for this price discount. Hybrid research will undoubtedly make advances in lowering seed price, improving quality, and expanding the knowledge of appropriate agronomic management. The speed and breadth of those advances will determine the potential of this technology, which will in turn have significant implications for the nature of the rice seed industry.

IRRI has recently developed a Hybrid Rice Development Consortium (HRDC), whose objective is to support hybrid rice research at IRRI and in national research programs and to serve as a source of information and germplasm. Public research organizations that are members of the HRDC have free access to designated hybrid breeding lines at various stages of development. Private members (mostly national companies and MNCs) pay an annual contribution, the level of which determines the extent of access to particular classes of germplasm and other benefits. The consortium strategy recognizes that hybrid research is being conducted by a wide range of players. Large companies and large public research institutes have extensive breeding programs and would simply include HRDC germplasm in their research; smaller companies and national programs may rely more heavily on the HRDC germplasm to develop their hybrids. The relative success of these different strategies will play a role in determining the future structure of the hybrid rice seed industry. Differentiated products from public programs and small companies will be more likely to be marketed through a diverse set of seed companies, including ones serving local markets, while more rapid success by the bigger players will likely result in more concentration, with fewer firms and varieties in the hybrid rice seed market.

Rice hybrids are currently less in evidence outside of Asia, although in the U.S. the company RiceTec sells hybrid rice seed and also has a presence in the Latin American seed market. In 2007, about a quarter of the rice planted in Arkansas (the leading rice producer in the U.S.) was hybrids (University of Arkansas 2007).

Issues for the future

The past several decades have seen significant changes in rice seed provision in Asia and elsewhere. Although the majority of rice seed provided in the Green Revolution era was the product of public programs, the early 21st century includes a much wider range of rice seed provision strategies. These feature a diversity of private-sector players, some redefined roles for the public sector, and increased attempts to address the needs of rice growers who have not benefited from the formal seed sector. A recognition of this diversity of seed providers and seed users is necessary in order to identify the most effective and equitable path of seed system development in the coming years.

In many countries, the policy changes of the 1980s and '90s have broadened the options for rice seed provision. Small and medium-size companies have been established to produce and market seed of field crops, including rice. This has helped develop the local agribusiness sector and has provided additional income-earning opportunities for contract seed growers and input dealers. Other options have also appeared, such as rice seed production by cooperatives (e.g., India) or by large NGOs (e.g., Bangladesh). In addition, there has been more attention to exploring ways in which farmers in more isolated or marginal environments can have better access to seed of appropriate varieties.

Despite the significant changes in rice seed provision, public-sector rice breeding still occupies a key position, and even many of the new hybrids are products of public research. But, public breeding programs need to adjust in order to accommodate to the changing nature of seed markets. There are fewer instances in which public varieties are automatically ushered into a public seed delivery system; instead, public plant breeders need to become acquainted with the seed enterprises that can deliver their products to farmers. The advent of PVP and hybrid technology opens opportunities for public breeding to protect its products and earn royalties from their sale. Policies need to give clear guidance on the commitments of public research for serving all members of the farming community and achieving a balance between revenue generation and ensuring widespread access to public rice varieties. If the success of public breeding and the ability to provide a continuing stream of new varieties are going to be increasingly determined by private seed delivery, then mutual expectations for performance need to be carefully defined. The seed producers will ask the research institute to provide good-quality source seed and information about new varieties, and the research institute must ensure that its new varieties are reaching all of the relevant farmers. The growth of private seed delivery is not, by itself, a guarantee of more rapid variety turnover; a study in India showed that both public and private seed companies tended to concentrate on the older varieties that farmers were familiar with, rather than investing in the promotion of newer releases (Pal et al 2000).

Even those countries that maintain large public rice seed delivery programs will need to think about their options and ensure that they are pursuing the most effective course of action. Such programs are often justified by national food security concerns, and may be jealously protected by political interests. Policymakers need to ask whether they are providing the widest possible range of rice varieties to meet farmers' needs, and whether they are doing this in the most efficient way possible. The era of highly subsidized seed programs has passed, but pricing policies can still affect the direction and efficiency of seed provision. Subsidies that encourage the use of certain types of seed (such as current support in some countries for hybrid promotion) may either help to introduce farmers to new technology or distort the allocation of agricultural resources, and attempts to control seed prices may increase access to certain types of seed or discourage further investment.

One of the major uncertainties about the future of rice seed provision is the possible impact of new technology. Hybrids are a prime example. Hybrid rice is still at a fairly preliminary stage, and it benefits from considerable policy support and encouragement in several countries. The exact extent to which hybrid rice seed will be taken up by farmers in various environments is yet to be determined. But, because a breeding program for hybrids requires more resources than one for conventional varieties, and hybrid seed production is also considerably more demanding, there is a tendency for hybrid development to be captured by larger research programs and companies. Progress made in breeding and seed production research will determine how widely accessible the technology will eventually be. In one scenario, the technology will allow the development of a wide range of hybrids by both the public and private sector and the concomitant development of a range of seed companies serving various markets. But an alternative scenario might see most of the activity concentrated in the hands of a few large commercial players, with less opportunity for meeting the more diverse needs of farmers.

Similar questions can be asked about biotechnology and the way that transgenic traits will be developed and made available. In one scenario, public breeding programs may license their transgenes or transgenic varieties to diverse seed companies. An alternative scenario would see most transgenic traits owned by a few MNCs that not only monopolize the technology but also control a significant proportion of the downstream seed industry. The availability of transgenes will also be likely to increase attempts to limit farmer seed saving, either through the establishment of strict IPR regimes or the increased use of hybrids.

These concerns about the future of rice seed provision have important implications for the equity of rice technology development. A more diverse and responsive seed sector can make important contributions to meeting the needs of a wider range of rice growers. But the seed provision strategies that are chosen help determine the type of farmer that is reached by new technology. If incentives for rice breeding shift strongly to the private side, this will affect the type of technology that is developed and the type of farmer that is served. Many rice farmers are still not reached by public seed programs or private enterprises, and there are no easy answers to the challenges presented by market isolation and highly localized variety requirements. The policies in support of particular seed provision strategies should take account of both the imperative for equitable rural development and a careful examination of the contribution of rice production to household livelihoods in specific environments. As rural economies in Asia develop and diversify, some rice producers in marginal environments will find alternative sources of income (on- or off-farm), but it would be unacceptable to have them pushed in that direction by an absence of reliable seed sources. As sub-Saharan Africa strives to increase its rice production, a sustainable rice seed strategy that links the public and private sector can help contribute to the development of robust national seed industries that strengthen the agribusiness sector and also promote rural development by providing productive technology to the majority of farmers.

The policy choices for achieving an efficient and equitable rice seed sector are complex and must take account of a number of factors. The farming environment is obviously an important determinant; intensive, irrigated rice farming environments will likely depend more on private-sector seed provision than those environments where rice is produced principally for household subsistence. In addition, the opportunities for private seed provision will depend in part on the general strength and diversity of the wider agricultural economy; the demand for various types of crop seed will influence the incentives for commercial rice seed production, and policies can favor (or restrict) opportunities for smaller seed companies that may address more diverse needs. The performance of new technology will also influence the direction of seed sector development. The extent to which new conventional varieties, hybrids, or transgenics actually offer worthwhile productivity gains will determine how much farmers are willing to pay for these innovations and who is likely to provide them. The increasing ability to protect many of these technologies means that particular attention must be given to guarding against monopoly control. And, the extent to which responsive seed-provisioning strategies emerge will depend crucially on farmers' ability to voice their concerns in the voting booth and the marketplace.

Thus, it is still necessary to seek the optimum mix of public and private contributions to formulating national rice seed provision policies. These policies should take advantage of the growing diversity of seed production alternatives, strengthen the connections of public plant breeding to the most appropriate delivery options, acknowledge the growing presence of private plant breeding, establish IPR regimes that reward technology developers but allow a level playing field for all innovators, and build farmers' skills and knowledge for participating in the seed market. In this rapidly changing technological and economic environment, the future of rice seed provision is not clear, but at least there is an expanding range of innovations and a wider set of seed provision options to choose from.

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Notes

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Fertilizer use, markets, and management

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Fertilizer and rice production

The role of fertilizers in rice production

Total fertilizer nutrient consumption ($N + P_2O_5 + K_2O$) worldwide reached about 169 million tons in 2007 (IFA 2009a). Total consumption for most countries with significant rice areas increased continuously in the last 50 years, and this trend is also probably valid for fertilizer use on rice. For the whole of Asia, fertilizer consumption rose from 3.8 million tons in 1961 to 92.3 million tons in 2007 (FAOSTAT 2009). In the same time period, fertilizer consumption increased from 0.6 million tons to 19.1 million tons in South America and from 0.7 million tons to only 3.9 million tons in Africa. The only countries with a large rice area and a consistent negative trend of total fertilizer consumption were Japan (a decreasing trend since the early 1980s) and Republic of Korea (a decreasing trend since the late 1990s). The only two countries in Africa with a significant rice area and considerable total fertilizer consumption were Egypt (1.6 million tons in 2007) and Nigeria (0.2 million tons in 2007).

Comprehensive statistics for crop-specific fertilizer consumption are available only for very recent years (IFA 2009a) although less comprehensive data are available for 2002 and 1999 (FAO 2002, 1999). They indicate that, in 2007, about half of all fertilizer used worldwide was applied on cereals, whereas the other half was used on oilseeds (about 10%), fruits and vegetables (17%), and other crops (together 23%). Most cereal fertilizer is applied on maize, wheat, and rice in almost equal shares (Table 1).

The development of fertilizer use on rice in selected countries during the current decade indicates that fertilizer consumption is still increasing in most developing economies (China, India, Vietnam, Indonesia, and Bangladesh), whereas it seems to be stagnating or even decreasing in "developed" economies (the U.S., Japan, Republic of Korea, and Europe). However, consumption has stagnated in Pakistan, the Philippines, and Myanmar (Table 2). Fertilizer use on rice in selected countries that represent 93% of total nutrient use on rice in 2007 is shown in Table 3. These countries accounted for only 82% of the total rice area in that year, signifying that fertilizer use on the remaining rice area is on average lower. Important rice-producing countries not included are Japan, Republic of Korea, Myanmar, Cambodia, Nigeria, and Nepal. By far the biggest fertilizer consumers for rice are China (9.2 million tons) and India (6.7 million tons), followed by Indonesia, Bangladesh, and Vietnam, with consumption around 1.5 million tons for each; all other countries consume less than 0.5 million tons for rice cultivation. However, the estimation of fertilizer rates per hectare shows that the highest users, with more than 200 kg ($N + P_2O_5 + K_2O$)/ha, are the U.S., China, Vietnam, Egypt, Malaysia, Turkey, and Chile. Average rates between 100 and

Table 1. Area, average yield, and fertilizer use for different cereals worldwide and share of total global fertilizer use in 2007.

Crop	Area (million ha)	Yield (t/ha)	Total fertilizer use ($N + P_2O_5 + K_2O$)		Total N use		Total P_2O_5 use		Total K_2O use	
			(% of total)	(million tons)	(% of total)	(million tons)	(% of total)	(million tons)	(% of total)	(million tons)
Maize	158	5.0	15.3	25.8	16.8	16.9	12.4	4.9	14.2	4.1
Wheat	214	2.8	15.1	25.5	17.3	17.4	16.2	6.4	6.0	1.7
Rice	156	4.2	14.4	24.3	15.6	15.7	12.3	4.8	13.3	3.8
Other cereals	–	–	4.8	8.1	5.1	5.1	5.1	2.0	3.3	0.9
Total			49.7	83.8	54.8	55.1	46.0	18.1	36.7	10.6

Sources: IFA (2009a), FAOSTAT (2009).

Table 2. Fertilizer use on rice for selected countries.

	$N + P_2O_5 + K_2O$ (million tons)			
Country	2001[a]	2002[a]	2006[b]	2007[b]
China	6.54	8.17	8.90	9.17
India	5.06	4.71	6.31	6.73
Bangladesh	1.31	1.40	1.49	1.47
Vietnam	1.31	1.38	1.47	1.51
Indonesia	0.92	1.11	1.28	1.40
Brazil	0.32	0.33	0.45	0.44
Thailand	0.21	0.21	0.41	0.35
Japan	0.42	0.54	0.36	–
Pakistan	0.29	0.30	0.34	0.32
U.S.	0.31	0.31	0.30	0.35
Republic of Korea	0.29	0.28	0.29	–
Philippines	0.27	0.25	0.25	0.26
Myanmar	0.16	0.12	–	–
Malaysia	0.06	0.06	0.18	0.19
Egypt	0.11	0.11	0.13	0.13
EU 27	0.11	0.12	0.09	0.10
Argentina	0.02	0.02	0.02	0.02

[a]Source: Estimated based on total fertilizer use from FAOSTAT data (last updated 2009) and mean fertilizer fraction applied to rice from 2006 to 2007 according to IFA (2009a). [b]Source: IFA (2009a).

Table 3. Fertilizer use on rice including total rice area, average yields, and estimated mean rates for selected countries at the global level in 2007.[a]

Country	2007 fertilizer use for rice (000 tons)			2007 rice area (000 ha)	2007 average yield (t/ha)	Mean fertilizer use (kg/ha)			
	N	P_2O_5	K_2O			N	P_2O_5	K_2O	Total
China	5,632	1,800	1,736	29,230	6.35	193	62	59	314
India	4,390	1,432	903	44,000	3.21	100	33	21	154
Indonesia	1,168	112	119	12,166	4.69	96	9	10	115
Bangladesh	1,159	172	137	11,200	3.88	103	15	12	130
Vietnam	772	454	286	7,305	4.87	106	62	39	207
Pakistan	266	53	3	2,600	3.19	102	20	1	123
Thailand	262	69	15	10,360	2.69	25	7	1	33
U.S.	255	45	45	1,112	8.05	229	40	40	309
Philippines	212	36	12	4,250	3.76	50	8	3	61
Brazil	146	143	154	2,901	3.88	50	49	53	152
Egypt	113	21	0	668	9.97	169	31	0	200
Malaysia	90	47	53	660	3.38	136	71	80	287
Iran	75	24	7	630	5.56	119	38	11	168
EU 27	46	17	31	606	5.77	76	28	51	155
Argentina	17	3	2	164	6.55	106	18	12	212
Russia	14	5	1	189	3.31	74	26	5	105
Turkey	12	5	1	85	8.06	141	59	12	212
Mexico	6	2	2	71	4.93	85	28	28	141
Chile	2	2	2	27	5.28	75	75	75	225
Total	14,637	4,442	3,509	128,224		114	35	27	176

[a]Source: All data on fertilizer use by country in 2007 is based on IFA (2009a), rice area and yield data are based on FAOSTAT data, and both were used to estimate fertilizer use per hectare.

200 kg/ha are used in India, Indonesia, Bangladesh, Pakistan, and Brazil; very low rates (<100 kg/ha) are used in Thailand, where relatively lower-yielding high-quality varieties are common, and the Philippines. Unbalanced fertilizer use (i.e., a dominant use of N fertilizer) seems to occur especially in Indonesia and Pakistan and to a lesser extent also in Bangladesh, the U.S., and Egypt.

Comparing country averages of applied N rates and yields shows that yields increase with increasing N application but that the efficiency of N fertilizer use varies considerably between countries (Fig. 1). The graph suggests very high partial factor productivity of N (grain yield per N applied) in countries with a small, well-developed rice area and temperate climate conditions in the rice-cropping season (e.g., Egypt, Turkey, Europe, Argentina). High to normal N-use efficiency was found in Vietnam and Indonesia, whereas relatively low N-use efficiency occured in India, Pakistan, China, and Malaysia. The reasons for low N efficiency can be manifold, including, for example, excessive N application (possibly in China) or a high percentage of rainfed rice area with multiple yield-limiting stresses (e.g., India).

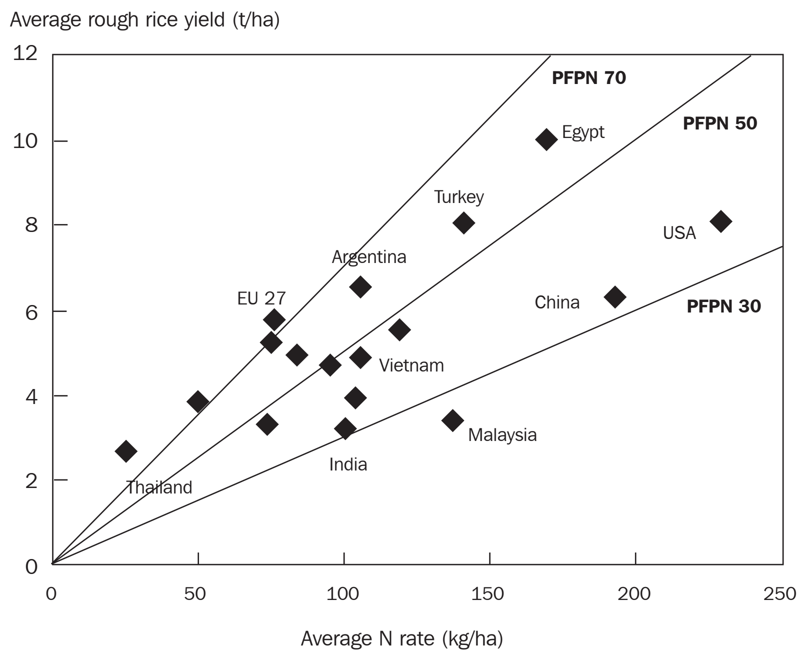

Fig. 1. Average N-use efficiency for selected countries. Data source is Table 3, and added are envelope lines of high, normal, and low partial factor productivity of N (PFPN of 70, 50, and 30 kg rough rice yield per kg N applied, respectively).

Fertilizer as a contributor to yield growth

Total rice area increased by only 0.49% annually between 1987 and 2007 (FAOSTAT 2009). Yields increased 1.31% annually and changes in irrigation accounted for an estimated 0.3% of this total annual increase. Increased use of fertilizer has been a major factor contributing between one-third and one-half of yield growth in developing countries since the start of the Green Revolution (Bruinsma 2003).

In the past decade, fertilizer use has continued to grow in developing countries by 3.6% per year, and it is estimated that this is contributing around 0.6% per year to yield growth (Fischer et al 2009). Growth through intensification and increased fertilizer use is no longer important in industrial countries and in some Asian countries fertilizer use is already high. Environmental concerns regarding externalities may increasingly restrict fertilizer overuse. In sub-Saharan Africa, neither irrigation nor increased fertilizer use have been important productivity factors, with almost static yield levels and increased production arising from increased cultivation area. In the last decade, a declining trend in rice total factor productivity is evident in some intensive rice areas of South Asia such as Punjab (Kumar et al. 2008). Improved nutrient-use efficiency at the farm level will be a requirement for improved fertilizer contributions to total factor productivity.

The need of rice for added fertilizer nutrients

Supplies of nitrogen (N), phosphorus (P), and potassium (K) from the soil, crop residues, irrigation water, and biological N_2 fixation are often insufficient to sustain high rice yields, making the application of fertilizer N, P, and K essential for profitable rice production. Nitrogen is the most limiting nutrient and some rice soils that have a high capacity to fix applied phosphate require early, high applications of P (Linquist and Sengxua 2001). Deficiencies of secondary nutrients (S, Ca, and Mg) and micronutrients (Cl, Na, Fe, Mn, Cu, Mo, B, Co, and Si), except for Zn, are generally less frequent for rice and often limited to specific soils. The roles of major, secondary, and micronutrients in rice production are well known and defined (Dobermann and Fairhurst 2000).

Nitrogen fertilizers and future costs

Nitrogen fertilizer use on rice accounted for between 12% and 15% of the total global fertilizer N use of 100 million tons per year in 2007. Approximately 67% of this N is produced and used as urea, the most concentrated solid N fertilizer. Urea use on rice accounts for an estimated 85% of rice fertilizer N—10.8 million t. Future projections of total global N fertilizer use vary from a modest increase from 100 million tons per year in 2007 to 121 million tons by 2050 (Wood et al 2004) to 155 million tons by 2070 (Frink et al 1999), respectively, representing annual growth of 0.5% and 1.1%. These very subjective projections represent more than a halving of the growth in the past decade and much will depend on improvements achieved in N-use efficiency, which is likely to be driven by higher energy prices.

The global fertilizer industry is increasingly concentrated in regions with access to least-cost feedstock and raw materials, which account for 70% to 80% of direct production costs. Ammonia production is the basis for all N fertilizer production. Natural gas (NG) accounts for 67% of the hydrocarbon feedstock for ammonia production and coal accounts for 26% (Prud'homme 2009). A ton of ammonia requires 28–31 gigajoules of NG and a ton of urea 18–19 gigajoules of NG. The technological efficiency limits of hydrogen separation from hydrocarbon feedstock have been reached (IFA 2009b) but current research into the use of molybdenum, silicon-tantalum, and zirconium catalysts for reforming ammonia may result in lower pressure and temperature requirements for the Haber-Bosch ammonia production process, thus reducing plant construction costs and energy use at some time in the future. Meanwhile, NG prices are rising, and each US$1 increase per gigajoules adds $18 to $19 per ton of urea, and these cost pressures will likely continue for the foreseeable future. Climate change legislation restricting greenhouse gas emissions will also add to ammonia and nitric acid production costs. Capital investment recovery in new ammonia-urea production plants today adds more than $100 per ton to the cost of urea and the increasing quantities traded (i.e., more than 30% and rising) add to transportation costs for many markets. By 2060, it may not be unrealistic to anticipate delivered urea costs increasing from a base of $300 per ton to between $600 and $700 per ton in real terms, reversing the downward trend in real N prices experienced over the past 50 years. This will create a significant incentive to improve N-use efficiency for the production of rice and other crops.

Phosphate fertilizers, future availability, and cost

Phosphate fertilizers are derived from phosphate rock (PR). Three countries account for 65% of PR production: China (29%), the U.S. (19%), and Morocco (17%). Total world phosphate fertilizer production is around 38 million tons P_2O_5 per year and 80% of this is based on phosphoric and sulfuric acid production. Increasingly, phosphate rock is processed at or close to mine sites and processed phosphate fertilizers are exported to world markets.

To date, 80% of PR used for fertilizer production has been high-quality, sedimentary rock, but the quality and reserves available are declining. Future expansion of PR production will be concentrated in North Africa and China. Recent estimates (Cordell et al 2009) using the Hubbert Curve, which predicts declining production of oil and other mineral resources when half of the reserves have been exploited, indicate peak production by 2034. However, uncertainty exists concerning the estimated level of global reserves. The cost of extracting, beneficiating, and processing igneous PR is higher than with sedimentary PR, and it can therefore be expected that the real costs of PR and phosphate fertilizer will increase over the next 50 years. Lower-quality rock can add 30% to 40% to the cost of producing phosphoric acid. Assuming that 30% of phosphoric acid will be produced from lower-quality PR by 2050, the average real cost of phosphoric acid would increase by about 10%. The market adjustment is going to be difficult and favor additional production mainly from existing large sedimentary PR processors with access to lower-quality rock. As with N fertilizers, these cost increases will provide incentive to lower fertilizer processing costs and improve field-use efficiency.

Potash fertilizers, future availability, and cost

There is no shortage of potash resources for fertilizer production but these resources and production are even more concentrated than either N or P, with 76% of production accounted for by Canada, Russia, Belarus, and Germany, and more than 80% of the 30 million tons of annual potash use represent international trade. Any disruptions to mining, processing, or distribution have a significant short-term impact on international prices. After a 30-year period of relatively low potash prices around $100 per ton for muriate of potash (MOP), there was a large spike in 2007-08 to $1,100 per ton and then prices settled to around $350 per ton in 2009 as demand fell in response to the very high prices.

The cost of mine development has risen considerably. Canadian data indicate an investment cost of more than $2.8 billion for new mine development, excluding infrastructure, and 10-year development lead times. Although there are large increases in planned production expansions, including new mine developments, it can be expected that most capacity expansions will be at existing sites, where development costs can be 40% of new site costs. Pressures on production costs will remain into the future and the ability for the industry to rapidly respond to upward demand fluctuations will be limited.

The need for improved fertilizer efficiency

The anticipated long-term N and P fertilizer production cost increases and persistence of increased potash production prices raise serious questions concerning the continued economic use of fertilizers at current application rates, even without considering potential needs for increased rates to raise productivity. Increased production and distribution costs can be offset to some extent by improved market efficiency, especially in Africa, and by improved policy environments in some of the smaller Asian markets, but far more cost reduction can be achieved by improved nutrient-use efficiency from improved field management of existing products and new-product technology.

Under current rice-farming practices in Asia, about one-third of the fertilizer N applied to irrigated rice grown on submerged soils is taken up by the rice crop. About one-third of the fertilizer N remains in the soil at crop harvest and about one-third of the added N is lost as gas to the atmosphere, mostly through ammonia volatilization (Buresh et al 2008). The recovery efficiency of fertilizer N (RE_N) can be increased with improved fertilizer N management although it typically remains below 50% in farmers' fields (Witt and Dobermann 2004). The recovery efficiency can be lowered by abiotic and biotic stresses, and it decreases at very high applications of fertilizer N.

Fertilizer market efficiency

Policy distortions, subsidies, and improvements

Twelve of the major Asian fertilizer markets are closely regulated by government controls and market-distorting policies are caused by fertilizer subsidies and other instruments. This situation was exacerbated by the global 2007-08 fertilizer price spike and economic crisis. The Fertilizer Control Order of India, which has governed that country's fertilizer sector since the 1960s, treats fertilizer as a strategic commodity. This created positive support for fertilizer production and market demand but at an unsustainable cost. In 2008, the Indian fertilizer subsidy cost was around $24 billion. Low subsidized prices for urea unmatched by similar levels for P and K created a situation of unbalanced fertilization, with excessive use of N and underuse of P and K. The N-P-K ratio in India in 2007 is estimated at 6.6-1.1-1 and on rice at 5.9-0.8-1. Recent changes to the subsidy policy that were aimed at improving the balance in nutrient use remain, with distorted low urea prices. Subsidized prices in China have contributed to overuse of fertilizer on rice (and other crops), with average application rates of 310 kg nutrients per hectare and a ratio of 8.5-1.5-1.0. By comparison, the ratio in the unsubsidized Thai market is estimated at 6.0-1.4-1.0.

Reducing marketing transaction costs in Asia and sub-Saharan Africa

In spite of the market distortions created by government policies in many of the major rice-producing countries, there is an increasing trend toward more conducive policies that encourage competitive and efficient markets. Thailand provides an excellent example of an enabling policy environment and market efficiency. Open, intensely competitive markets, supportive business and financial services, and a strong agricultural extension service provide farmers with products, technology, and output markets in a least-cost manner. Imported urea supply costs are summarized in Figure 2 for 2006. Thai rice farmers were paying between 40% and 90% less for urea imported

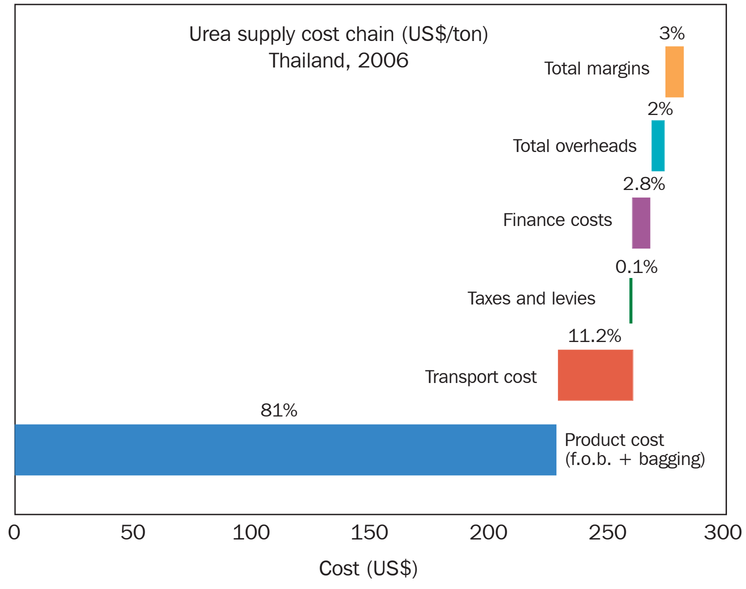

Fig. 2. Cost components of imported urea in Thailand, 2006. Source: Chemonics International and IFDC (2007).

from the Arab Gulf than small farmers in coastal eastern African countries (Chemonics International and IFDC 2007).

Liberalization of domestic markets in China combined with continued state control over trade through variable tariffs and trade taxes has enabled Chinese farmers to be isolated from large international fertilizer price swings and has encouraged fertilizer use to the extent of overuse. Fertilizer production and markets in Bangladesh, Indonesia, and other Asian countries continue to be strongly influenced by central government controls and lack the economic allocation function of market pricing.

Poor infrastructure, weak institutions, and poor farm policies create obstacles to the adoption of new technology. These factors and thin fertilizer markets apply almost universally throughout sub-Saharan Africa and lack of farmer incentives to use and restricted access to timely supplies of fertilizer constrain fertilizer use, in addition to the high fertilizer-to-grain price ratios, which on average are double those in other regions (Morris et al 2007). In South and East Asia, many of these market constraints have been overcome, although the emphasis has been on services to irrigated agriculture while dryland crop production areas lag far behind.

Fertilizer types and implications

Historically, straight fertilizers such as urea, triple superphosphate, and muriate of potash were used by the majority of smallholder rice farmers in Asia together with crop residues and other available organic matter, including green manure crops. More recently, there has been an increase in the use of compound and blended fertilizers containing N, P, and K together that provide added convenience and labor saving for application but add to the nutrient unit costs. When this additional cost is more than offset by more balanced application of nutrients, benefits accrue from additional yield per investment in fertilizers.

The increasing use of diammonium phosphate (DAP) as the phosphate source for both direct application and as an N and P source in blended fertilizer reduces the application of sulfur (S). Progress is being made in adding S to DAP and other high-analysis fertilizers and zinc coating of urea is providing a convenient means of addressing zinc deficiency.

Organic sources of nutrients (i.e., organic fertilizers) have been promoted for rice in Asia often as a response to rising prices of commercial manufactured fertilizer and misperceptions about environmental degradation in intensive rice production (Dobermann and Dawe 2008). The promotion of organic fertilizers has often failed to fully appreciate the bulkiness and low nutrient content of organic materials, the often negligible benefit of organic materials on the physical properties of submerged rice soils, and the typical mismatch between the ratios of nutrients in organic materials and the ratios of nutrients needed by rice.

The application of organic materials does not seem essential for sustaining organic matter and N-supplying capacity in submerged soils with continuous rice cultivation (Pampolino et al 2008). Organic amendments can play a more important role on poor soils with very low soil organic carbon contents and in water-limited, rainfed rice environments. Organic fertilizers and retained crop residues can supply appreciable K to rice, but they rarely supply enough N to meet the needs of a rice crop (Buresh et al 2010). Because organic materials have small or negligible environmental or sustainability benefits in lowland rice production, their use should be governed largely by profitability as a source of supplemental nutrients.

Current economics of fertilizer use on rice

The addition of fertilizer nutrients is a major cost in rice production, typically accounting for 15% to 30% of total production costs (Moya et al 2004, Pampolino et al 2007) depending upon government subsidies and labor costs. The economic return to fertilizer use depends on two factors: the ratio between fertilizer (input) and rice (output) price, and the yield increase per amount of fertilizer (or nutrient element) used. But both of these factors in turn depend on several other parameters, of which only the most important ones are considered here.

Figure 3 shows the ratio of the most widely used fertilizer materials in rice cultivation and the rice price at the international level, which is less affected by national policies and economic conditions (all data from the IRRI database; http://beta.irri.org/solutions). Since 1960, all fertilizer materials became more expensive relative to rice price, but most increases in the nutrient-rice price ratios for urea and DAP have occurred since the early 1990s. Therefore, the general trend on international markets indicated a reduced profit from fertilizer use.

However, this trend is not necessarily valid at the farm gate because national policies and markets can modify fertilizer as well as rice prices. This is indicated by Figure 4, which shows the development of the urea-N to rough rice price ratio at the farm gate for some important rice-producing countries. In several countries, N fertilizer was quite expensive relative to the rough rice price until the late 1980s, probably because of import taxes, supply limitations, and strong demand. By 2000, the farm-gate urea-N to rough rice price ratio in the countries ranged between 1.7 and 3. However, in the last few years, fertilizer again became more expensive in several countries, including Vietnam and the Philippines (recent data were not available for Bangladesh, Indonesia, and Thailand). Thus, the clear trend of increasing relative fertilizer costs at the international level (Fig. 3) is blurred at the farm gate (Fig. 4), but the farm-gate urea-N to rough rice price ratio has increased recently in at least some countries.

Production economics at the household level

Rice farmers in traditional systems relied on organic materials such as farmyard manure, crop residues, compost, and various green manure plants to increase plant available nutrients and maintain soil quality. Since the introduction of synthetic manufactured fertilizers, the use of organic materials declined continuously, mainly because synthetic manufactured fertilizers need less labor and are economically more attractive to farmers (Pandey 1999). However, this development differs between systems: farmers use much more fertilizer and very little organic material in favorable irrigated systems, whereas they use little synthetic manufactured fertilizer and considerable amounts of organic materials in unfavorable rice-based systems. These trends are clearly indicated by the survey data presented in Table 4. The data also show that the average returns to

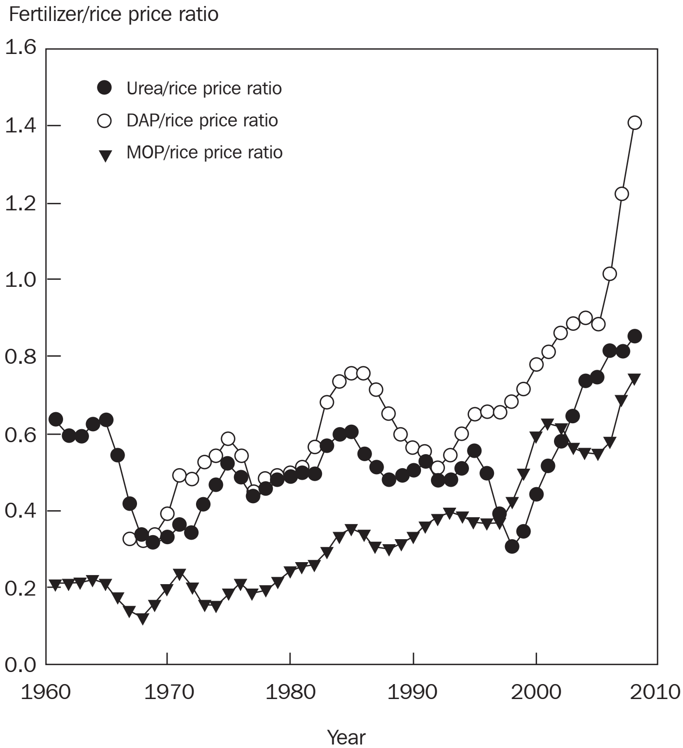

Fig. 3. The development of the fertilizer-rice price ratio based on international prices between 1960 and 2008. Shown is the 3-year moving average; the data used are the urea price valid for Europe, the DAP price valid for U.S. Gulf ports, the muriate of potash (MOP) price valid for Vancouver/Canada, and the international milled rice export price.

Table 4. Average fertilizer use and respective returns in rice by ecosystem in selected Asian countries.

Ecosystem	No. of plots	Yield increment[a] (t/ha)	Fertilizer increment[a] (kg nutrient/ha)	Average fertilizer use[b] (kg nutrient/ha)	Incremental net returns to fertilizer (US$/ha)	Relative incremental net profit (%)
Irrigated lowland[c]	493	2.93	139	123	460	98
Rainfed lowland[c]	1,215	1.09	54	47	258	73
Rainfed upland[c]	533	0.07	9	7	7	3

[a]Increments were calculated based on farmers using none or very small quantities of fertilizer for each ecosystem relative to the sample average. [b]Overall average of fertilizer use (N+P+K). [c]Source: IRRI farm-level surveys of different ecosystems conducted between 2003 and 2008 in Indonesia, Nepal, Philippines, and Vietnam (irrigated lowlands), Cambodia, India, Indonesia, Lao PDR, Nepal, Thailand, Vietnam (rainfed lowlands), and India, Lao PDR, Nepal, and Vietnam (rainfed uplands).

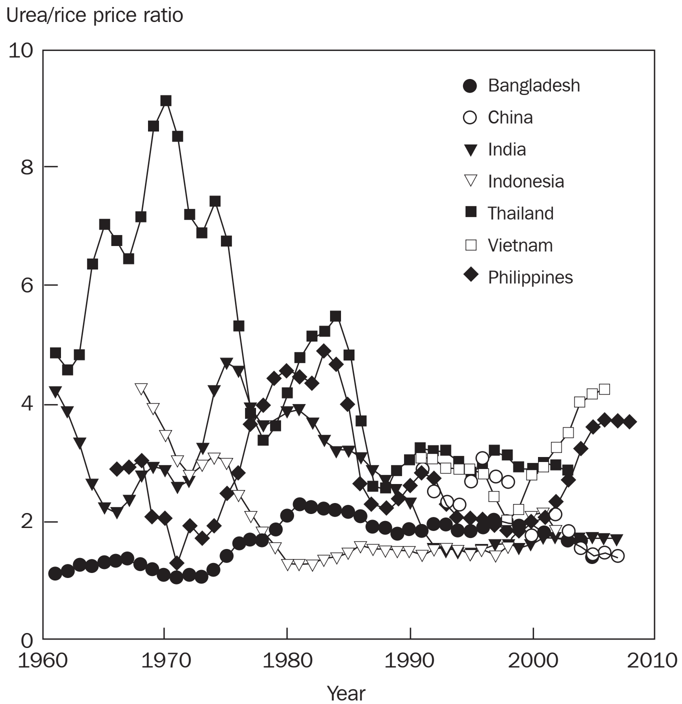

Fig. 4. The development of the urea-rice price ratio at the farm-gate for selected important rice-producing countries between 1960 and 2008. Shown is the 3-year moving average; the data used are the domestic retail prices of N from urea and the farm-gate harvest price of rough rice.

fertilizer use in rainfed lowlands are smaller as compared with irrigated lowlands, in both absolute and relative terms. The usual reasons for lower returns to fertilizer use in rainfed systems are more frequent abiotic stresses (e.g., drought, flooding) and less fertile soils (e.g., low cation exchange capacity, salinity, and acidity). Furthermore, the survey showed that the relative contribution of fertilizer costs to total cash production costs was on average only 14–15% in rainfed environments, whereas it was about 33% in irrigated systems. Irrigated rice farmers made about twice as much profit per hectare than rainfed farmers.

Unbalanced nutrient applications to match plant requirements are an important cause of low fertilizer-use efficiency. More visible responses to N applications and the higher costs of P and K are most often underlying causes. Both Asia and Africa have an excessive use of N in relation to both P and K, as illustrated in Figure 5. Good management such as using the best available varieties, proper weeding, optimal fertilizer rates, properly balanced ratios of added nutrients, and appropriate fertilizer timing can improve fertilizer-use efficiency.

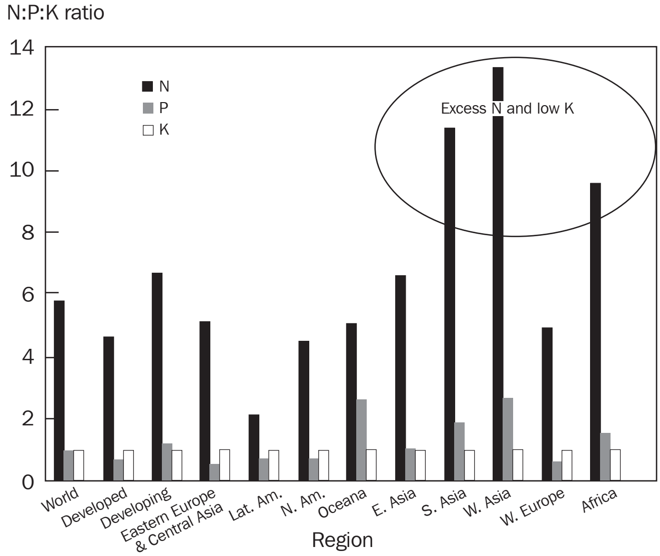

Fig. 5. Regional nutrient ratios for fertilizer use in different regions. Source: IFA (2009a).

The actual profit from fertilizer use depends on the costs of all fertilizers used (e.g., N, P, K, organic fertilizers), other inputs needed (labor for fertilizer and for the harvest/postharvest treatment of the additional grain yield), and investment costs (interest rates on credit). Complete partial budget analyses for fertilizer use in rice are rare but the general assumption is that farmers use fertilizer when the value per cost ratio is at least 1.5 to 2.

Improving nutrient-use efficiency through site-specific nutrient management (SSNM)

Much of the rice in the tropics and subtropics is produced on relatively small landholdings, which can vary across short distances in historical fertilizer use, yield attainable with farmers' management practices, retention of crop residues, and growth duration of rice cultivars. Blanket fertilizer recommendations for large areas or agroecological zones fail to account for these variations, which affect the need of rice for supplemental nutrients. Further improvements in productivity and profitability from fertilizer use consequently require approaches and algorithms for tailoring fertilizer use to the field-specific needs of rice.

Algorithms for determining fertilizer recommendations are often derived from factorial fertilizer trials conducted across multiple locations. SSNM for rice, as developed by IRRI with national organizations across Asia, is an alternative approach for dynamic management of nutrients to optimize supply and demand of a nutrient within a specific field in a particular cropping season (Dobermann et al 2002, 2004). It aims to increase the profitability of rice farming by achieving higher rice yield per unit of fertilizer invested.

The SSNM practices developed and evaluated in farmers' fields in 1997-99 increased yield and profit as compared with farmers' fertilizer practices (FFP) (Dawe et al 2004). The profitability of SSNM—as determined in on-farm trials from the difference in gross returns above fertilizer costs (GRF) for SSNM compared with FFP—averaged \$38 to \$82 per hectare at six of the eight irrigated rice areas studied across six Asian countries. Subsequent on-farm trials with irrigated rice in 2002-03 revealed a mean 7% increase in grain yield with SSNM compared with FFP across locations in India, the Philippines, and Vietnam (Pampolino et al 2007). Annual GRF for two rice crops as determined from focus group discussions at these locations averaged \$107 per hectare per year higher for farmer collaborators previously evaluating SSNM compared with farmers with no previous involvement with SSNM (Pampolino et al 2007).

Additional on-farm evaluations from 2001 to 2004 across four locations in three countries for both high- and low-yielding seasons consistently revealed higher yields for SSNM than for FFP (Fig. 6) (Buresh et al 2006). On-farm trials with wet-seeded rice in the Philippines in 2007 revealed yield gains averaged across two growing seasons of 0.6 t/ha or 13% with SSNM compared with FFP (Gabinete et al, unpublished data). The added net benefit from SSNM averaged \$109 to \$130 per hectare per season depending upon the seed rate for direct-seeded rice.

Principles of N management

During the past 20 years, emphasis on the parameter of N-use efficiency has evolved from recovery efficiency of fertilizer N (RE_N) to increased agronomic efficiency of fertilizer N (AE_N), which is the increase in grain yield per unit of fertilizer N applied. This emphasis on the output per unit of input without compromising on the need for high yield acknowledges the importance of ensuring increased profit for farmers (Buresh 2007). The greatest opportunities for rapid widespread improvements in AE_N in farmers' fields exist with optimizing fertilizer N rates to match the yield gain to applied fertilizer N and splitting the application of fertilizer N to match crop needs for supplemental N at critical crop growth stages.

With SSNM, the required fertilizer N is apportioned in several doses during the growing season to ensure that N supply matches crop need at critical growth stages. The leaf color chart (LCC) is an inexpensive and simple tool for monitoring the relative greenness of a rice leaf as an indicator of leaf N status (Alam et al 2005, Witt et al 2005). A standardized plastic LCC with four panels ranging in color from yellowish green to dark green has been developed and promoted across Asia (IRRI 2010b).

Principles of P and K management

The recovery efficiency of fertilizer P (RE_P) in farmers' fields typically averages about 15% to 30% for irrigated rice but the nonrecovered P is not mobile and adds

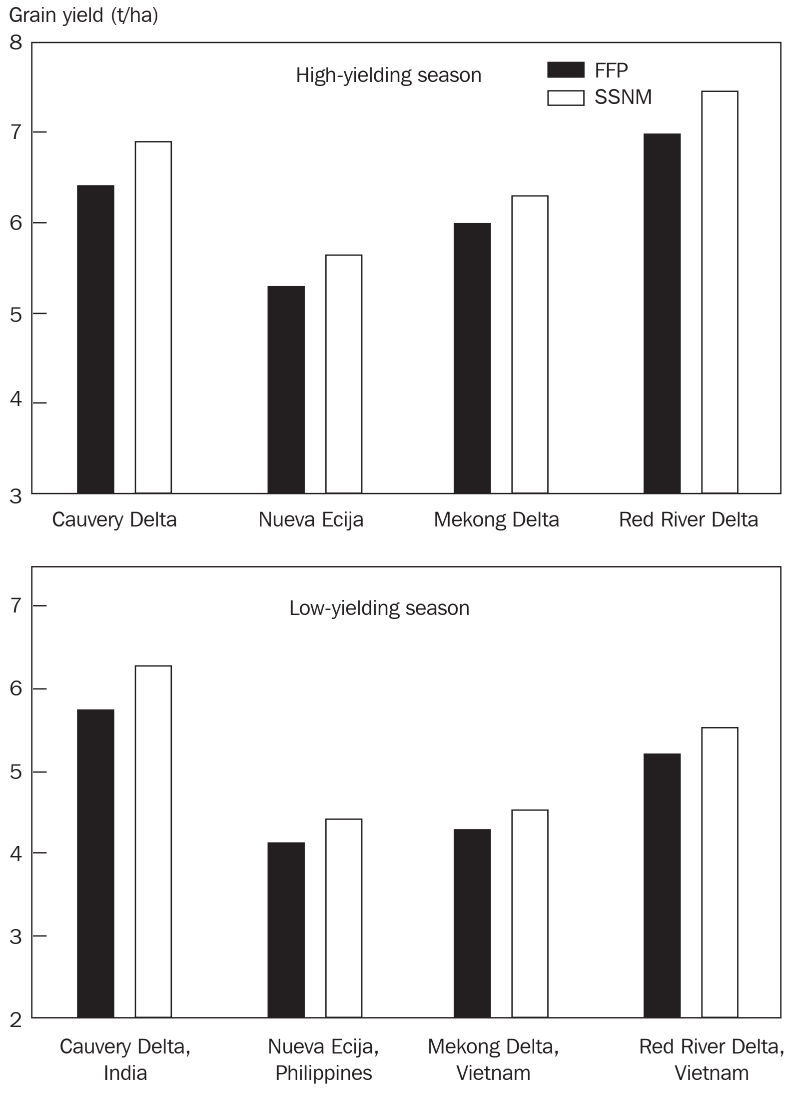

Fig. 6. Grain yield obtained from on-farm trials comparing site-specific nutrient management (SSNM) with farmers' fertilizer practice (FFP) at four locations in 2001-04. Yields were significantly higher at *P* value<0.05 for SSNM then FFP for all combinations of seasons and locations.

to the indigenous P in the soil. The recovery efficiency of fertilizer K (RE_K) varies greatly in farmers' fields. Although it can average 50% to 60%, it can also be relatively low when yield gain to applied nutrient is negligible. RE_P averaged 25% and RE_K averaged 44% in an on-farm evaluation of SSNM for irrigated rice across Asia (Witt and Dobermann 2004). RE_P of about 30% and RE_K of about 60% can be targeted in rice-growing environments with ample water and good crop management practices. Target efficiencies for rainfed environments could be lower.

Fertilizer P and K requirements for a specific field are determined with SSNM using estimated target yield, nutrient balances, and expected yield gains from added nutrient. When yield gain to P or K is negligible, fertilizer P or K requirements are derived solely from the estimated nutrient balance (i.e., nutrient inputs relative to nutrient removal by the crop). When yield gain to applied P or K is certain, fertilizer P or K requirements are determined from a combination of the nutrient balance and anticipated yield gain to nutrient application (Buresh et al 2010).

Nutrient needs for rice affected by water limitations

Most rice is grown on soils with continuous or prolonged periods of submergence leading to anaerobic soil conditions. This causes a tremendous change in soil biogeochemical characteristics, with mostly positive effects on plant availability of nutrients (Kirk 2004). After submergence, the soil pH-value tends to change toward neutral, affecting the availability of most nutrients positively. Subsequent adsorption and desorption reactions often lead to an increased availability of calcium, magnesium, and potassium. The changing soil redox reactions bring about the release of occluded and adsorbed soil P and ammonium becomes the major form of N present. The water layer also prevents any water limitation, and biological N_2 fixation in the floodwater and soil can contribute considerable N (Buresh et al 2008).

These benefits are of course not available or only partly available to rice systems without submerged soil conditions or with alternating wet and dry conditions (rainfed lowland rice and some irrigated areas). In the absence of submergence, the soil dries and becomes aerated. Soil aeration alters soil biogeochemical processes, often leading to a reduced supply of plant-available N and P, reduced Zn and Fe availability on high-pH soils, and increased P fixation. In addition, water-limited conditions reduce P availability more than other elements (Kirk et al 1998), making higher fertilizer-P rates necessary in drought-prone fields.

Limited or no water control in rainfed rice systems also has consequences for fertilizer management. It is a widespread practice in Asia and Africa to topdress a considerable fraction of the total urea into the water layer in the early vegetative phase and at panicle initiation. Optimal uptake and response to these applications require correct timing, which depends on crop phenology and sufficient field water resources at the application time. In rainfed systems, drought or flooding in the field might prevent optimal timing, the application might be conducted with too much or too little water in the field, or this might not be possible at all. Another difference is that traditional-type varieties are still widespread in many rainfed environments. For example, high-quality rice from traditional-type varieties is grown on millions of hectares in northeastern Thailand. These varieties have a much lower yield potential than modern semidwarf varieties and they need considerably lower fertilizer rates (Haefele et al 2006).

This short overview of some important characteristics and processes in rainfed systems shows the generally less favorable conditions for crop growth and nutrition in these environments. However, the basic principles of SSNM as well as the need for field-specific nutrient management are equally valid in rainfed lowlands and similar water-limited systems (Naklang et al 2006, Haefele et al 2006). Despite lower potential or attainable yields in rainfed than irrigated environments, the yield gain from applied nutrient—and hence need for fertilizer—is not necessarily lower for rainfed than for irrigated systems (Haefele and Bouman 2009, Haefele and Konboon 2009). But, fertilizer rates need to be adjusted to the average attainable yields, the production risk caused by abiotic stresses (e.g., drought, flooding, and salinity), and the local fertilizer-to-grain price ratios (Haefele et al 2010).

Secondary nutrients and micronutrients

Deficiencies of secondary nutrients (S, Ca, and Mg) and many micronutrients (Fe, Mn, Mo, B, Co) are often less frequent for rice and are often limited to specific soils. Acid soils, such as Acrisols, with very low base saturation at the exchange complex can have a positive response to the application of Ca and Mg carbonates (Goswami and Banerjee 1978). Response to Fe application can sometimes be observed on calcareous soil or in nonflooded rice systems, and response to Cu (copper) occurs, especially on organic soils (Dobermann and Fairhurst 2000). Deficiencies of Zn are mostly limited to alkaline soils but are becoming more common in many intensive systems, especially when most crop residues are removed and mainly high-analysis N and P fertilizers are used. Similar trends are reported for S and Si (silicon).

Increased use of concentrated fertilizers containing little or no S has led to S deficiency in rice crops, especially when crop residues are burned or removed. Management of S nutrition of rice depends on the production system. Under upland conditions, S nutrition of rice is little different from that of other crops. Under flooded conditions, several factors can induce S deficiency. These include shallow rooting; reduction of sulfate to sulfides, some of which are toxic (H_2S) and others low in solubility (FeS, ZnS); and slower mineralization of organically bound sulfur. Sulfur fertilizer is most effective when applied at sowing or transplanting (Blair and Lefroy 1998). Sulfate S application 2 weeks after transplanting has been shown to be effective (Dobermann and Fairhurst 2000) but delaying application until maximum tillering is not effective for treating S deficiency (Blair and Lefroy 1998). Recent work compared elemental S, S-coated DAP, Monoammonium phosphate (MAP), Triple Superphosphate (TSP), and urea with gypsum in both surface and deep-placed applications on upland and flooded rice. Elemental S and S-coated urea were the most effective in providing the highest recovery of fertilizer S in the plants, followed by S-coated phosphate fertilizers (Yasmin et al 2007). Incorporation of elemental S in high-analysis phosphate fertilizers is possible and may be a means of ensuring adequate S fertilization in flooded-rice production systems.

The submergence created for rice cultivation influences electrochemical and biochemical reactions, and alters pH, pCO_2, and the concentration of certain ions. This environment increases the availability of Fe and Mn with a concomitant decrease in Zn and Cu. Sodic and upland soils and calcareous coarse-textured soils with low organic matter content suffer from Fe deficiency, besides Zn and Cu deficiencies.

Amending the soil with the required amount of Zn before transplanting is effective and easy to adopt, compared with repeated foliar sprays of 0.5% $ZnSO_4$ or the use of Zn-enriched seedlings through seed soaking in 2–4% $ZnSO_4$ solution, fertilizing the nursery with Zn, or seedling root dipping in 2% ZnO slurry. Hepta- as well as mono-hydrate $ZnSO_4$ are better than other sources of Zn (ZnO, $ZnCl_2$, and Zn frits). Zinc-blended diammonium phosphate (Zn-DAP), superphosphate, and nitrophosphates have also proved effective. Zinc-enriched organic manures (farmyard manure, greenleaf manure, and coir pith compost) have been found advantageous for the direct and residual crops. Zinc fertilization, when required, with an optimal dose of 25 kg $ZnSO_4$/ha once every two to eight crops yields high economic returns (Fairhurst et al 2007). Rice cultivars do not experience deficiency of B and Mo (Savithri et al 1998).

Uptake of improved nutrient management in rice farming

Improved management of conventional fertilizer

Putting SSNM into practice. The tailoring of fertilizer management to field-specific conditions is relatively knowledge-intensive because many factors, including crop yield, crop residue management, historical fertilizer use, use of organic materials, nutrient inputs in irrigation water, and growth duration of the variety, can all influence fertilizer management. This knowledge intensity has slowed the wide-scale promotion and uptake by farmers of best management practices based on SSNM principles. Adoption by farmers can also be constrained by confusion arising from contrasting recommendations for nutrient management received from different organizations and technical experts.

The widespread use of field-specific nutrient management by farmers requires transforming the knowledge-intensive principles of SSNM into locally adapted nutrient best management practices. Extension workers, crop advisors, and farmers require locally adapted guidelines that enable them to rapidly identify and implement nutrient best management practices for specific fields and rice-growing conditions.

The SSNM-based approach can be used to determine fertilizer N, P, and K requirements for a specific growing season and rice field based on estimates of the attainable target yield, nutrient balances, and probable yield gains from added nutrient. These estimates can be obtained for a specific growing season and rice field from responses to about 10 to 15 questions regarding historical rice yields, rice variety, crop rotation, fraction of crop residue retained, occurrence of sediment deposition from flood events, and landscape position. Computer-, Web-, and mobile phone–based tools can be used to acquire the responses to the questions, use the responses with

SSNM-based principles to determine fertilizer requirements, and then provide a personalized guideline with application times and amounts of fertilizer sources for a specific rice field. Such decision tools are now available with training materials and videos to facilitate the uptake by farmers of best management practices based on the SSNM concept (IRRI 2010a, b).

Decision tools for extension and farmers. Through an IRRI-coordinated partnership of public- and private-sector organizations in the Philippines, the results from more than a decade of research on SSNM for rice were used in 2008 to develop and verify decision support software titled *Nutrient Manager for Rice* for extension workers and farmers. A partnership of organizations in Indonesia likewise developed decision support software titled *Pemupukan Padi Sawah Spesifik Lokasi* (*Location-Specific Rice Fertilization*), which was tailored to rice production for the country. In the Philippines, *Nutrient Manager for Rice* was also released in 2009 as a Web version in English and five dialects of the Philippines (IRRI 2010a).

The experiences from the Philippines and Indonesia in transforming the scientific principles and research findings of SSNM into tools such as decision support software, videos, and quick guides for accelerating the uptake of nutrient best management for rice provide a model for replication in Asia and Africa. As of February 2010, additional decision tools for providing field-specific best nutrient management were under development and verification for rice in Bangladesh, China, India, Vietnam, and West Africa (IRRI 2010b).

Modified nitrogen fertilizer products

Many modifications to urea have been proposed to overcome losses of urea-N and the assessment of potential economic benefits has been reported (Buresh and Baanante 1993). Benefits vary considerably between product modifications depending on their cost, the cost of urea, and the value of rice. A brief summary of some product modifications is provided below.

a) <u>Urea deep placement</u>

Urea deep placement (UDP) is a method of fertilizer application that substantially increases N uptake efficiency in rice with a single application of N fertilizer. Large urea supergranules of 1.8 up to 2.7 g in weight were developed specifically for deep placement in rice production. The briquettes are applied by hand within 7 days after transplanting at the rate of one briquette for four hills. The placement of fertilizer near the root zone of the plant reduces N losses that occur from surface-applied (broadcast) methods and the efficiency of N fertilizer increases (Savant and Stangel 1990, 1998, Mohanty et al 1999). UDP also reduces nitrification-denitrification losses because of the placement of the fertilizer in the anaerobic layer. In addition to yield increases from 20% to 25% over conventional urea application (Fig. 7) and the above advantages, deep placement has the following benefits:

– One-time N application because ammonium-N exists in the proximity of the placement site, which maintains availability of the required N throughout the vegetative and grain formation stage of rice plants.

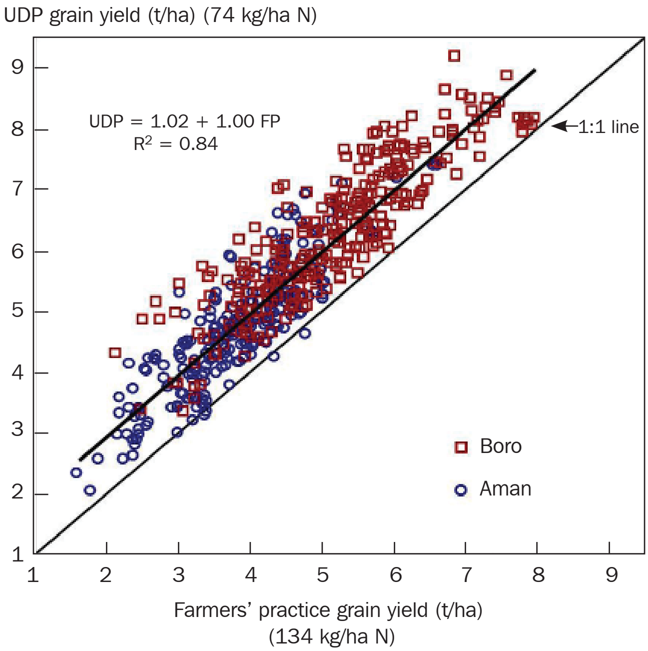

Fig. 7. Comparison of the effect of management with the farmers' fertilizer practice using conventional NPK and with urea deep placement (UDP) on rice yields In Bangladesh.

- Less weeding because of N placement in the rice root zone (Fig. 8). In general, this may even offset the additional labor required for deep placement.
- It helps promote biological N_2 fixation in the floodwater due to very low N concentration in the floodwater.
- N content in the straw is higher; straw is more nutritional for livestock.
- It helps decrease air pollution because of low gaseous loss of N.
- It helps decrease water contamination because of less runoff loss of N.

UDP is highly desirable for conditions that promote high ammonia volatilization and runoff losses—soils with more than 20% clay, low permeability and percolation rates, low ammonium sorption, and environments with poor crop establishment (prolonged transplanting shock) and heavy rainfall. UDP is unsuitable for sandy soils because of high leaching loss.

However, UDP technology has not been widely adopted by rice farmers for a multitude of reasons. Even in Bangladesh, where the technology has been widely promoted and developed, only 6% of the total rice crop used UDP in 2008. A lack of briquette supplies, the increase in direct seeding, and the relatively low cost of urea until recent years and reduced availability of rural labor may have all played a role in the slow adoption process. Until recently the absence of strong institutional support has also been a factor in the slow adoption process.

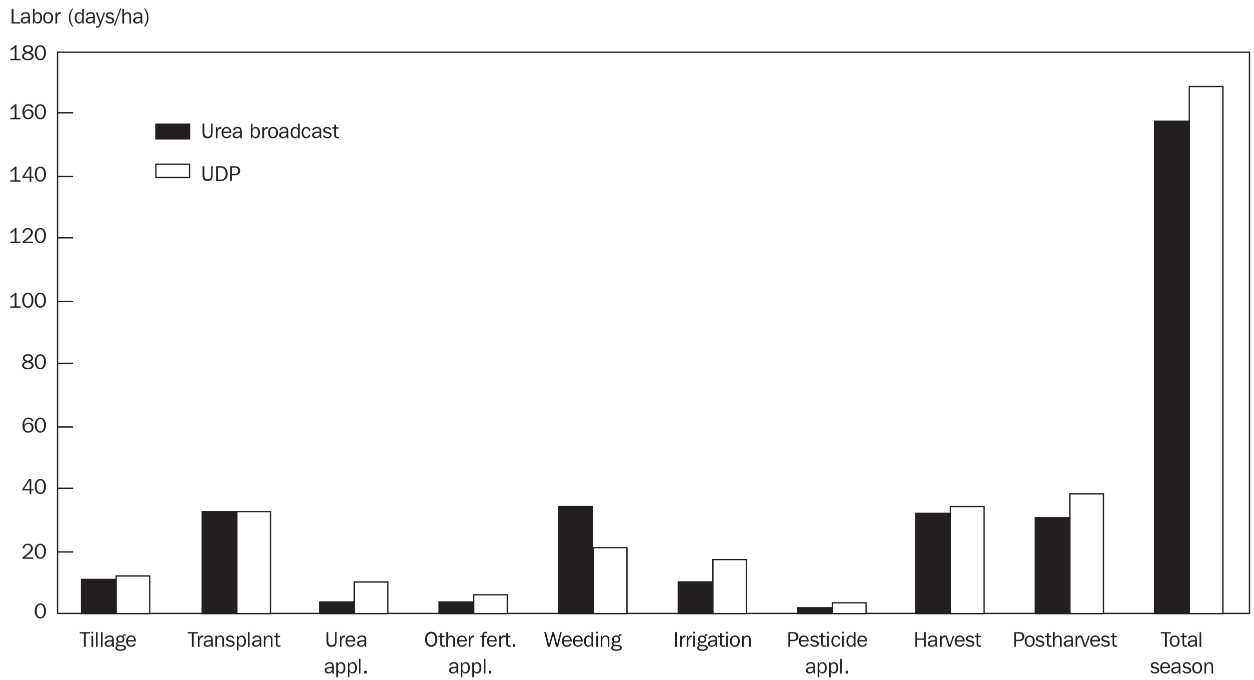

Fig. 8. Comparison of labor requirement for rice production with broadcast application of urea and urea deep placement (UDP). Source: Thompson and Sanabria (2010).

Khan et al (2009) compared the performance of UDP and the recommended use of conventional urea with the LCC in two seasons (aman and boro) for two years in a total of 456 farmers' fields in Bangladesh. All crop and fertilizer management, except for N management, was identical in the two treatments. Rice yields in both seasons were statistically identical for UDP and conventional urea managed with the LCC. Added net returns relative to the farmers' fertilizer practice were comparable for UDP ($39 per hectare) and conventional urea with the LCC ($56 per hectare) averaged across the two aman seasons, and higher for urea with the LCC ($106 per hectare) than UDP ($78 per hectare) averaged across two boro seasons (Table 5). Management of conventional urea with the LCC favored individual farmer benefits, and UDP favored national benefits, that is, less urea imports or production from scarce natural gas.

The recent developments such as the use of larger urea briquettes (1–3 g in size); inclusion of P, K, and micronutrients depending on site-specific requirements (Kapoor et al 2008); the manufacture and availability of briquettes at the village level; and the participatory development of mechanized applicators that reduce manual labor requirements by two-thirds have given renewed impetus to UDP technology.

b) Inhibitors and slow- and controlled-release products

Nitrogen fertilizers containing urease inhibitors may restrict ammonia volatilization loss by delaying the hydrolysis of urea to ammonium. The effectiveness of the most researched urease inhibitor for rice, N-(n-butyl) thiophosphoric triamide (NBTPT), varied widely among rice soils (Byrnes and Freeney 1996). The stabilized NBTPT

Table 5. Effect of N management with the leaf color chart (LCC) and urea deep placement (UDP), as compared with the farmers' conventional fertilizer practice (FP), on rice yield, fertilizer use, cost, and net returns during aman and boro seasons across two years in Bangladesh.

N management practice	Grain yield (t/ha)[a]	Fertilizer use (kg/ha)[a]			Yield increase (t/ha)[b]	Cost increase (US$/ha)[b]	Net returns (US$/ha)[b]
		N	P	K			
Aman season							
FP	3.6 b	101 a	0 b	0 b			
LCC	4.4 a	88 ab	12.5 a	50 a	0.8*	76 ns	56 ns
UDP	4.3 a	51 b	12.5 a	50 a	0.7*	77 ns	39 ns
Boro season							
FP	6.3 b	153 a	19 a	34 b			
LCC	7.1 a	104 b	23 a	67 c	0.8+	49 ns	106*
UDP	7.0 a	77 c	23 a	67 c	0.7*	53 ns	78+

[a]Means within a column for a season having the same letters are not significantly different at the 0.05 level of probability. [b]*and + indicate significance at 0.05 and 0.10 level of probability from FP, respectively. ns = not significant at 0.10 level of probability from FP.
Source: Adapted from Khan et al (2009).

inhibitor (Agrotain®) has given a 10–20% increase in rice yield. Recent laboratory evaluation of Agrotain® on a wide range of flooded soils showed that total ammonia volatilization loss after 17 days was 1.8 to 7 times lower for urea + Agrotain® than for urea alone (unpublished IFDC data).

For irrigated lowland and favorable rainfed rice, denitrification and leaching are not major N loss mechanisms. However, in rainfed rice with frequent drying and wetting cycles, and increased percolation (no puddling and lighter-textured soils), controlling the nitrification process and thus reducing leaching and denitrification losses could be an important component of N management. Highly water-soluble nitrification inhibitors such as dicyandiamide (DCD) were effective under upland conditions but had limited success under direct-seeded delayed flooded rice (Norman et al 1989). Nitrification inhibitors such as DCD, AgrotainPlus®, and 3, 4 dimethylpyrazole-phosphate (DMPP) might play a role in controlling nitrification-denitrification provided they are cost-effective.

Increased costs associated with coated fertilizers such as S-coated urea, Osmocote®, Nutricote®, Polyon®, and Environmentally Safe Nitrogen (ESN®) have limited their use to high-value crops. Rice yield increases of up to 20% and N recovery of 70–75% have been reported with controlled-release (Polyon® and Nutricote®) fertilizers (Singh et al 1995). On the other hand, preplant N application using controlled-release fertilizers (ESN® and Duration®) gave lower yields than conventional preflood urea application on direct-seeded rice (Golden et al 2009).

Modified phosphate fertilizer products

Controlled-release products. Most research and development on controlled-release fertilizers have been directed at N fertilizers. However, recent new products have concentrated on modifying the microenvironment interface of phosphate, soil, and plant roots.

Polymer coatings delay the release of water-soluble phosphate from the granule to reduce phosphate fixation; however, the temperature-sensitive release appears to be short-lived and the cost of polymer coating is high. Although no yield comparison results are available yet, this technology appears unlikely to be beneficial in flooded rice, and in warm environments, and might be better suited for high-value crops.

Another approach to improve phosphate efficiency is to surround the phosphate fertilizer granules with a high cation exchange capacity polymer, which forms a zone around the granules sequestering multivariant cations that normally form insoluble precipitates with water-soluble phosphate fertilizer. The effects are neither temperature nor pH dependent. However, the coatings add about 25% to the cost of the fertilizer and their use may be uneconomical for many rice production systems.

Phosphate-solubilizing microorganisms. Early work centered on the use of mycorrhiza fungi to increase the availability of phosphate to plant roots. Very few commercial applications were developed and benefits could be limited to nonflooded rice systems. Developments in genetic engineering may lead to future plant varieties that can directly use insoluble P from soils, but these possible developments may be a long way away.

Other technologies

The very recent but fast development of nanotechnology might also offer new opportunities in agriculture. Research into nano-encapsulation of plant nutrients by embedding plant nutrients in zeolites is being undertaken as an exploration of alternative means of providing slow-release plant nutrients. Zeolites are a group of naturally occurring minerals having a honey-comb-like layered crystal structure. The network of interconnected tunnels and spaces can be loaded with nano-particles of plant nutrients so that it acts as a reservoir for the nutrients that can be slowly released and matched to plant uptake. However, applicable technologies are not yet available.

Rice production and fertilizer use in Africa

Rice production in sub-Saharan Africa (SSA) is dominated by rainfed upland systems, and by mainly rainfed lowland systems in the inland river valleys, both characterized by no or very limited water management control. Some highly productive irrigated systems do occur, but the average farmer's yield is around 25% of the yield potential. Lack of mechanization, the use of unimproved varieties, poor weed control, and lack of fertilizer use all contribute to the poor on-farm performance.

Average fertilizer nutrient use in Africa, averaged for all crops, is only 8–10 kg/ha—about 5% of the world average. There are multiple reasons for this low use of fertilizer and underdeveloped agricultural input markets. A 2006 comparison between SSA and Asian fertilizer cost chains in Figure 9 illustrates how urea (and other fertilizer) costs are often 80% higher for African farmers than for those in Asia. The reasons for this include the small total market demand, the poor transport infrastructure and longer transportation distances, underdeveloped input market networks, the high cost and unavailability of credit, the absence of enforceable fertilizer regulations, and inconsistent policy environments. All of these factors result in higher cost supply chains for African farmers.

Development of New Rice for Africa (NERICA) varieties and concerted holistic rice development programs led by the African Rice Center aim at doubling rice production in 10 years. Reaching that goal should be facilitated by the Comprehensive African Agricultural Development Programme (CAADP), which calls for 10% of national budgets to be devoted to agriculture by 2015. With significant research and development efforts being made by national governments, international donor agencies, and international research centers, the constraints facing Africa's smallholder farmers, including rice producers, will hopefully be surmounted. Improved varieties and access to affordable fertilizer can then assist farmers in raising productivity in both rainfed and irrigated rice production.

A vision for the role of fertilizer in future rice production

Rice production now accounts for 10% of global fertilizer use and the main fertilizers used are determined more by the economics of manufacturing and logistics than by agronomic efficiency. Major fertilizer markets for rice in Asia are distorted by government

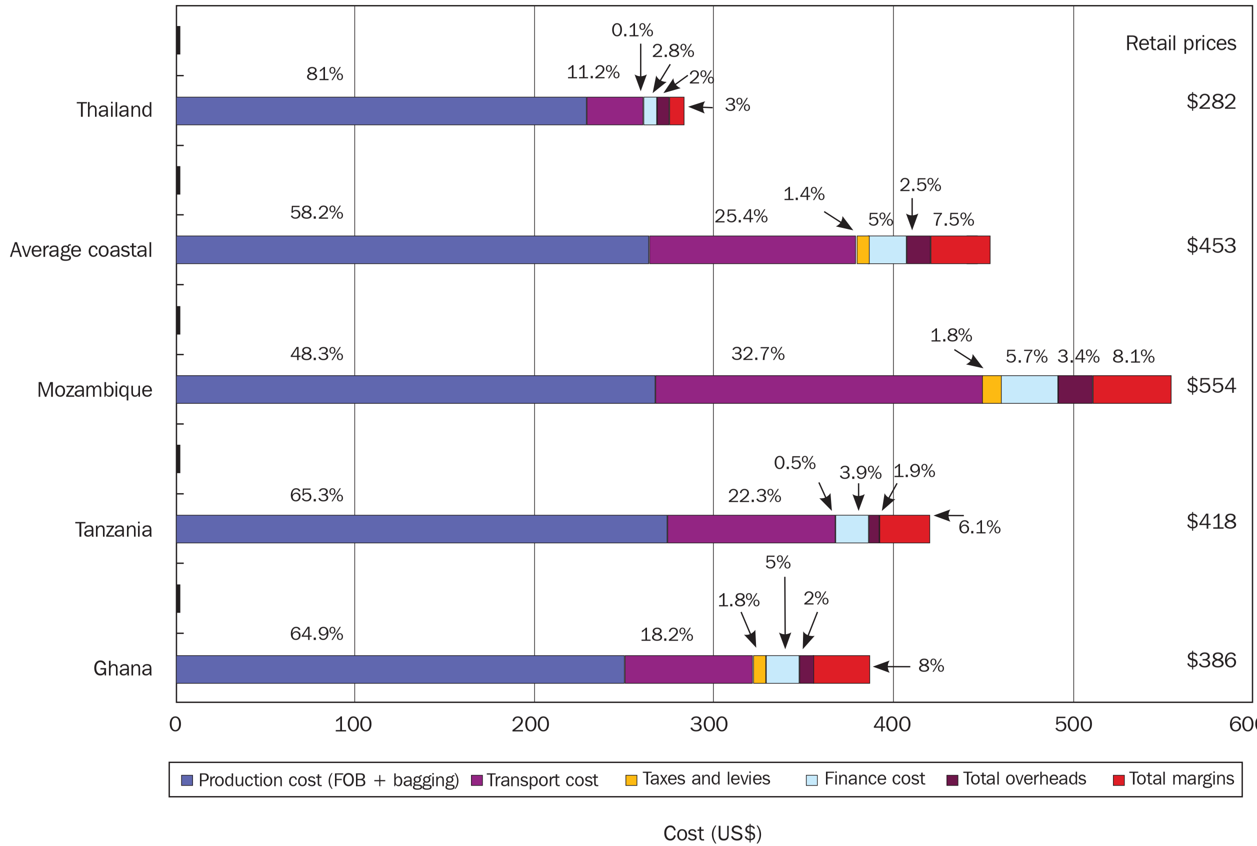

Fig. 9. Fertilizer supply chain costs comparing African coastal countries with Thailand In 2006. Source: Chemonics International and IFDC (2007).

pricing policies that encourage unbalanced and wasteful nutrient use. In sub-Saharan Africa, fertilizer use for rice production is severely constrained by underdeveloped marketing and infrastructure, and unfavorable fertilizer-rice price ratios. Generalized fertilizer recommendations and farmers' fertilizer management practices constrain the efficiency of nutrient applications and currently the manufacture, distribution, and use of fertilizer have many deficiencies and externalities detrimental to the environment. However, external fertilizer inputs will continue to be necessary to meet rice production needs for a global population of more than 9 billion people.

Broad changes foreseen for rice production and fertilizer use over the next 50 years include supply-side, climate, socioeconomic, and output market changes in farm production patterns that have implications for researchers, extension agents, fertilizer production and marketing, and policymakers. In sub-Saharan Africa, underdeveloped transportation infrastructure and fertilizer market systems add to the challenges on that continent to meet the growing demand for rice from local rice production systems.

Supply-side drivers

Manufacturing processes have reached scale and technical limits unless a new production process paradigm is achieved. Raw material resources for N fertilizers have increasing competition from growing energy demands and finite phosphate sources may become limiting within 50 years. Production costs will increase substantially, placing constraints on the economic use of fertilizer at the farm level. Some farm-gate cost reductions can be achieved through more efficient marketing systems but the brunt of improved efficiency must be borne by improved nutrient-use efficiency. Doubling nutrient-use efficiency should be an attainable target to be achieved through a combination of improved new or modified fertilizer products and more balanced site-specific nutrient applications augmented by new rice varieties that can use nutrients more efficiently and withstand stress better, and improved farmer knowledge of rice nutrition.

Current policies in China and India favor wasteful use of N by farmers and imbalance in nutrient use due to price distortions. Although difficult to alter, these policies are not sustainable and policy improvements can be expected over time that will have the effect of improving overall nutrient-use efficiency from more balanced nutrient applications.

In sub-Saharan Africa, drastic improvements are required to improve farmer knowledge and crop marketing that will incentivize an increased use of fertilizer and increase productivity not only for rice but for total food security. Similar improvements in the input marketing chain and financial services to agriculture and agribusiness are required together with longer-term investments in transportation to lower marketing costs.

Climate-change drivers

Rice production and nutrient management under changing climatic conditions with extremes of water and temperature conditions will lead to (i) rice production using less water with more aerobic soil conditions and drying-wetting cycles during crop growth, and (ii) more intensive crop production where water supplies are sufficient.

There will be more likelihood of secondary and micronutrient deficiencies under scenario (i) and increased nutrient extraction under more intensive production systems. The need for fertilizer products with multiple primary nutrients, secondary nutrients, and micronutrients will increase to meet these new demands together with secondary and micronutrient additions to primary nutrient products such as urea and DAP.

The need will increase for locally adapted field-specific management practices using available fertilizer sources and tailored products providing the most economic returns at acceptable risk. There will be an even greater need for field-specific nutrient management and increased needs for climate and market information and hence a greater role for information technology tools and professional crop advisors. This increased level of science- and economic-based inputs for fertilizer management decisions will create an increased demand for simple, innovative decision tools that can be used by farmers. This represents a major challenge to extension services.

Nitrous oxide emissions in rice systems will likely increase under increased soil drying-wetting cycles, shortages of water, and diversification of cropping systems because of more aerobic soil conditions. Reducing NO_x emissions from urea will become more important and will partially drive the need for product enhancements. Combined with higher energy costs, climate change will be a major driver in the research effort for fertilizers with enhanced efficiency.

Socioeconomic drivers

Production of rice with less labor on small-scale landholdings will induce more mechanization and possible changes in crop establishment from transplanting to direct seeding on either saturated soil (i.e., wet seeding) or unsaturated soil (i.e., dry seeding). This trend could be intensified by increased areas of rice production from landholdings professionally managed for absentee land owners.

Manual application of fertilizer represents a relatively small proportion of the total labor required in rice production, and the optimal timing and distribution of fertilizer are comparable for transplanted and direct-seeded rice. Provided labor is available to broadcast fertilizer N during the growing season, the single most important fertilizer management intervention to increase the yield gain and efficiency from fertilizer N is better timing the application of fertilizer N to match crop needs for supplemental N.

The uptake of drills enabling mechanized sowing and placement of fertilizer could stimulate the application of greater proportions of fertilizer N at the time of sowing. Mechanized application of fertilizer could be especially attractive in reduced-till production systems where mulches or the absence of soil submergence could limit the movement of broadcast fertilizer N into the soil. The absence of farm labor during the crop growing season due to migration or off-farm employment could also lead to a trend toward the application of a greater fraction of fertilizer N at or near crop establishment and reduced splitting of fertilizer N applications—a trend already apparent in parts of China as small farmers increase off-farm employment activities. These trends will drive the need for N management and sources of N, such as timed-release N fertilizers, that can meet crop needs for the entire growing season.

Output market drivers

The population-driven increased demand for food production, especially grains, together with improved nutritional standards and aspirations will act as drivers for intensifying rice production and improving quality. This will probably see more cereals in cropping systems, shorter fallows, and less tillage. These factors will have implications for nutrient transformations in the soil, especially with the increased expansion of water-saving production systems. Under these emerging conditions, farmer management of fertilizer nutrients will be assisted by the next generation of fertilizers that will need to be not only more efficient but also easier to use efficiently. These may include products with improved ammonification and nitrification inhibitors, modified nutrient release mechanisms, slower nutrient release characteristics, bio-coatings, host-specific and climate-driven release mechanisms, as well as biofortified fertilizers containing nutritional supplements of iodine, zinc, and iron.

Development priorities

With rice accounting for approximately 10% of all fertilizer use today and an expected increase in demand for rice (Timmer et al, this volume), some important priorities are apparent for research and development and extension on rice nutrition practices. Foremost among these are to get more out of the use with existing products. This will require intensification of extension to rice farmers on integrated soil fertility management, balanced fertilization practices, site-specific nutrient management, and simple, practical farmer-level tools to ensure improved management.

Current computer-, Internet-, and mobile phone–based decision tools that provide extension workers, crop advisors, and farmers with field-specific guidelines on nutrient management are only beginning to scratch the surface of what could be possible in the future with emerging information technology. Mobile phones are already capable of wireless banking, and connecting farmers to banks could open the doors for micro-financing, loans, and purchasing power that they have never had before. Emerging mobile phone applications for providing field-specific fertilizer guidelines (IRRI 2010a, b) could potentially link rice farmers through their phone to suppliers of fertilizer and financing options to purchase the fertilizer. Policies must be enacted to remove price distortions that encourage the overuse of N and discourage economical use of balanced, required nutrients at specific sites.

Fertilizer products with enhanced efficiency are required to reduce farm-level costs and reduce greenhouse gas emissions from rice fields. This will be a major area of future research. At present, polymer coatings are too expensive to be used economically under most circumstances for grain crops and alternative means to match nutrient release to crop nutrient uptake patterns are needed. Research programs that coordinate plant breeding with nutrient-use efficiency, stress tolerance, and herbicide and pest control traits will be important developments.

Improved marketing capacity, especially in sub-Saharan Africa, is required to ensure that the retailers of fertilizers and other inputs are better informed and more knowledgeable of product characteristics, best management practices, and farmer benefits. Government policies will generally need to be more supportive of the private sector in producing, procuring, distributing, and selling plant nutrients. This support will be best shown through policies that are conducive to private-sector business development, investment in transportation and communication infrastructure, the supply of market information, and regulation of the fertilizer sector.

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Notes

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Chapter 2.4

Managing irrigation in an environment of water scarcity

Randolph Barker, Ruth Meinzen-Dick, Tushaar Shah, T.P. Tuong, and Gilbert Levine

Introduction

More than 60% of the world's irrigated area is in Asia. Approximately two-thirds of that is devoted to cereal grain production: rice and, to a lesser extent, wheat. The irrigated area has expanded rapidly over the past half century through the construction of canals and storage dams and the exploitation of groundwater. This expansion can be regarded as a *sina quo non* of the Green Revolution. It occurred in two phases. With assistance of multilateral donor agencies, surface irrigation systems with large storage dams were constructed in the 1970s and '80s. This was followed from the 1990s onward by the explosion in the use of pumps largely with private funding to exploit and often overexploit groundwater aquifers.

In Asia, we have now entered an era of both land and water scarcity. The demand for water for nonagricultural purposes is growing. We face the need to manage our water resources more efficiently for both production and consumption. This will require changes in policies, technologies (including infrastructure), and institutions but, unfortunately, these cannot be achieved overnight. Furthermore, these changes must be (and in some instances have been) developed to fit highly varied conditions in time and space. As if this challenge were not enough, water resource managers must be prepared to meet climatic changes brought on by global warming (see Wassmann et al, this volume).

This chapter focuses on the development and management of water resources for irrigation in Asia over the past half century and the challenges facing the future. It traces the issues associated with the management of irrigation principally at the farm and system level, including related environmental problems. Of course, this must be put in the broader context of watershed management. In addressing irrigation, we take a holistic look at water for agriculture rather than strictly for rice since there are trade-offs between water used for rice and other crops and for agricultural and nonagricultural purposes. However, approximately 50% of the irrigation in Asia is devoted to rice and more than half of the rice area is irrigated. A major challenge is to identify the key options facing policymakers, irrigation system managers, and water users in a given location in deciding how to organize to achieve and sustain optimum use of water resources.

The expansion of irrigation since the 1960s

Asia has a long history of irrigation development to support rice production. Much of this was developed as small-scale community-managed systems, but there is also a long history of government investment in irrigation. (See, for example, Wittfogel 1957.) The majority of irrigation systems in Asia were designed to capture monsoon rains for paddy (wet rice) cultivation. Depending on the frequency and amount of monsoon rains and local topography, irrigation systems ranged from small-scale run-of-the-river systems with small diversion points, in which the primary storage was the paddy itself, to large-scale reservoirs that supplied hundreds of thousands of hectares.

Between the early 1960s and the mid-2000s, the net irrigated area (area served by irrigation, whether single or double cropped) in Asia doubled (Table 1). China and India together accounted for 70% of the growth. The proportion of the rice area irrigated, and particularly the area irrigated in the dry season, has been increasing. Irrigated area now represents 55% to 60% of total rice area. At the same time, the area of rice without water control declined. Huke and Huke's (1997) data for the early 1980s and mid-1990s (Table 2) show that the area in dryland (nonpuddled) and deepwater rice has been declining throughout Asia. Hijmans' (2007) estimations show that a large portion of the rainfed (puddled but not irrigated) area, approximately one-third of the total rice area, is flooded.

The expansion in irrigation, identified in Table 1, occurred in two distinct phases. The 1970s and 1980s witnessed large investments by countries with the support of foreign donors in government-managed gravity-flow irrigation systems. This trend is reflected in the global investment in large dams (Fig. 1). Much of the technology for large dam construction in Asia was borrowed from the American West (e.g., Hoover Dam in the 1930s). Today, the largest number of large dams is in China, where the focus is on hydropower. The investments in government-managed irrigation systems are much lower, and much of this is focused on the rehabilitation of existing systems. However, these supply-driven systems with their relatively poor control of water were well suited to the production of rice, particularly in the monsoon season, and helped to support the earlier adoption of Green Revolution technology in much of Asia.

In addition to surface systems, groundwater has played an increasing role in irrigation. Initially in South Asia, large tubewells were managed by the state or owned by larger farmers. Pump irrigation had been expanding in Pakistan and India for decades (Fig. 2). From the 1990s onward, the expansion has been driven by the adoption of cheap low-lift pumps, including both manual treadle pumps and small electric or diesel-powered pumps. This is sometimes referred to as "the groundwater revolution" (Shah 2009, Giordano and Villholth 2007, Barker and Molle 2005). However, it should be noted that pumps were also used (1) for pumping water in the major river deltas for both irrigation and drainage, and (2) to extract water from rivers or drains or recycle water within surface irrigation systems (Barker and Molle 2004).

In 1984, International Development Enterprises (IDE) made improvements on a locally manufactured treadle pump in Bangladesh and began promoting treadle pump technology. Treadle pumps were adopted widely, particularly by poor smallholders

Table 1. Growth in irrigated area of Asian regions, 1961-2006.

Country/region	Irrigated area (000 ha), period average			Irrigated area in 2006 as % of			Average annual growth rate in irrigated area (%)		
	1961-75	1976-90	1991-2006	Total harvested area, 2006[a]	Irrigated area, Asia 2006	Irrigated area, 1961	1961-75	1976-90	1991-2006
China	36,338	45,075	52,613	25	35	185	2.47	0.78	1.01
Indian subcontinent[b]	41,063	56,353	73,459	27	48	219	2.12	1.95	1.27
Delta countries[c]	4,887	8,717	13,948	23	10	430	4.10	3.96	2.06
Insular Asia[d]	5,375	6,274	6,828	10	4	133	0.70	1.24	0.04
East Asia[e]	3,986	3,924	3,577	64	2	95	0.99	–0.42	–0.74
Asia	91,649	120,343	150,425	24	100	204	2.22	1.52	1.14

[a]Harvested area includes cereals, citrus fruits, coarse grains, fiber crops, fruits, jute and jute-like fibers, oilcakes, oil crops, pulses, roots and tubers, tree nuts, vegetables, and melons. [b]Indian subcontinent includes India, Nepal, and Pakistan. [c]Delta countries include Bangladesh, Cambodia, Lao PDR, Myanmar, Thailand, and Vietnam. [d]Insular Asia includes Indonesia, Malaysia, the Philippines, and Sri Lanka. [e]East Asia includes Japan and the Republic of Korea.

Source: FAOSTAT.

Table 2. Rice area by ecosystem (000 ha).

Region	Irrigated	Nonirrigated[a]	Total	% irrigated
Huke (1982)				
East Asia	35,296	2,847	38,143	93
South Asia	17,152	36,116	53,268	32
Southeast Asia	11,671	22,452	34,123	34
Asia	64,119	61,415	125,534	51
Huke and Huke (1997)				
East Asia	31,134	3,040	34,174	91
South Asia	25,827	32,008	57,836	45
Southeast Asia	16,309	23,813	40,121	41
Asia	73,270	58,861	132,131	55
Hijmans (2007)				
East Asia	28,654	2,692	31,345	91
South Asia	27,141	30,050	57,191	47
Southeast Asia	18,138	24,922	43,060	42
Asia	73,933	57,664	131,596	56

[a]Nonirrigated includes dryland and deepwater rice.

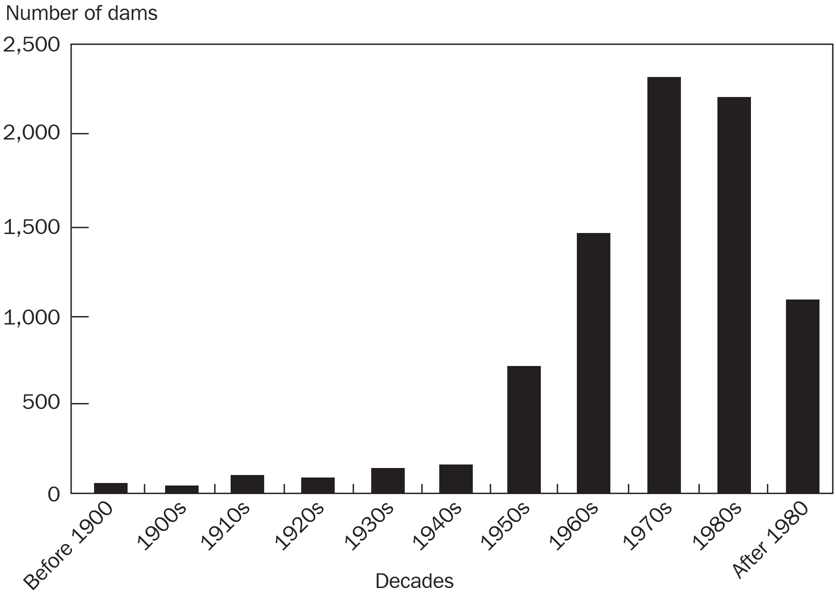

Fig. 1. Evolution of additional large dam construction in Asia (pre-1900 to post-1980). (The International Commission on Large Dams defines a "large dam" as one measuring 15 meters or more from the foundation to the crest.) Source: World Register of Dams: ICOLD, Paris, 1998.

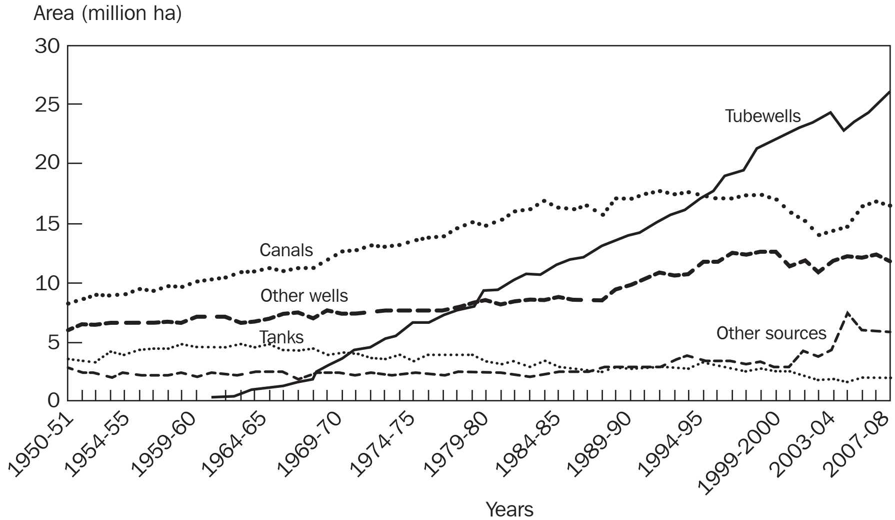

Fig. 2. Irrigated area by source, India, 1950-2009.

in the shallow water tables of Bangladesh and to a lesser extent in India and Nepal (Shah et al 2004). Also in the 1980s, China was developing a low-lift pump industry to serve its domestic market. In the mid-1990s, trade policies in many countries in South and Southeast Asia opened up markets to the import of pumps and engines. An export market that began with the smuggling of pump sets across the Vietnamese border soon blossomed with the new trade policies and the help of Chinese government policies to support exports (Huang Q et al 2007). In Bangladesh, the Chinese pumps soon replaced the treadle pumps and spread rapidly throughout Asia and beyond.

To understand where the pump technology has been having its greatest impact, it is useful to divide Asia's rice-growing area into four regions. As shown in Table 3A and 3B, the largest increase in rice production occurred early on in China, the Indian subcontinent, and insular Asia. Recently, however, the most significant growth in rice production has occurred in the region defined as the deltas. For example, in the Ganges-Brahmaputra Delta (Bangladesh and eastern India), pumps have made it possible to grow a second (boro or dry-season) crop, which in turn allowed the adoption of higher-yielding varieties. In the lower Mekong Delta (Vietnam), on the other hand, pumps facilitated the shift from one deepwater rice crop to two crops, one before the floods and one after the floods. The use of fertilizer increased. In Bangladesh, production more than doubled from 17.6 million tons of rough rice in 1975-76 to 37.6 million tons in 2000-01 (Hossain et al 2007). Overnight, Bangladesh moved close to self-sufficiency and Vietnam once again became one of the world's leading exporters of rice. In Thailand, the world's largest exporter, exports rose by 50%. Thus, we can conclude that low-lift pumps have shifted the historical comparative advantage in

Table 3A. Increase in rough rice production (000 tons) by decade, 1962-2009, for specified Asian regions.[a,b]

Time period	China	Indian sub-continent	Delta countries	Insular Asia	East Asia	Asia
1962-70	43,632	11,834	6,513	9,526	665	72,171
1971-80	29,674	13,919	12,872	13,434	–773	69,126
1981-90	35,072	35,250	15,386	14,529	1,186	101,423
1991-2000	1,308	26,157	36,791	8,257	–1,458	71,055
2001-09	13,345	21,229	25,700	14,438	–1,422	73,290

[a]Based on 3-year averages, computed as 1970 less 1962 production, etc. [b]See footnotes to Table 1 defining regions.

Table 3B. Percentage increase in rough rice production by decade, 1962-2009, for specified Asian regions.[a,b]

Time period	China	Indian subcontinent	Delta countries	Insular Asia	East Asia	Asia
1962-70	66	21	14	52	3	35
1971-80	26	21	25	48	–4	24
1981-90	23	42	23	33	6	28
1991-2000	1	22	44	14	–7	15
2001-09	7	16	21	21	–8	14

[a]Based on 3-year averages, computed as 1970 less 1962 production, etc. [b]See footnotes to Table 1 defining regions.

Asian rice production back to the deltas. Of course, this may not be good news in the long run as these deltas are the areas that will be affected by global warming. This would include changing flows from the rivers in the Himalayan watershed plus rising sea levels.

Elsewhere, particularly in those areas less abundantly supplied with water, pumps have been enabling farmers to shift to higher-value crops. Pumps are often located in the command areas of surface irrigation systems—*conjunctive use* but not *conjunctive management*—allowing "tail-end" farmers greater access to water. For example, the managers of surface irrigation systems typically do not know the number of pumps located in their command area and, as will be discussed later, a main function of surface irrigation systems is groundwater recharge.

Contemporary problems

In this section, we discuss both the achievements and problems associated with the development and management of surface-water and groundwater irrigation in Asia. This leads us to an examination of the externalities associated with irrigation development: on the positive side, ecosystem services and multiple uses; on the negative side, environmental concerns.

Surface irrigation development in Asia

Irrigation development in Asia can be traced back millennia, including both small-scale community-managed systems and systems developed by the state. Under the British in South Asia, systems were designed to be administered with a minimum of management decisions. Water delivery was predetermined in advance by the design of the outlets, with little or no farmer control. Cropping patterns were therefore often predetermined, with all farmers in an area growing either rice or dry-footed crops. But the inflexible administered systems did not stand the test of time in a dynamic physical, socioeconomic, and political environment.

In the late 1950s, Taiwan undertook a major improvement in irrigation infrastructure that allowed water to be rotated down to the 10-hectare level (VanderMeer 1980). This allowed farmers not only to use less water in growing rice, but to have the flexibility to grow crops other than rice. If you drive through the rural areas of Taiwan, you will see rice growing side by side with other crops. The Philippines tested rotation irrigation in the 1960s but had neither the infrastructure nor the management (nor the politics) to make it work, illustrating the importance of socio-technical aspects of irrigation.

Although government-managed systems in East Asia (excluding China) performed relatively well—due to a combination of responsive technology and agencies (Small and Carruthers 1991)—the record in South and Southeast Asia was marked with greater performance problems. From the 1960s onward, Shah (2009) notes that the ethos of "build-manage-maintain" gave way to "build-neglect-rebuild." Moreover, the fiscal crisis of the state in the 1980s meant that governments were no longer able to continue to subsidize irrigation maintenance, especially as increasing rice production was no longer as critical for national food security or economic returns to the state. As long as multilateral lending agencies and governments were willing to put money into "rebuilding," there was a strong incentive for the irrigation bureaucracies to let things deteriorate. Poor maintenance has led to poor water delivery, with the result that farmers have been reluctant to pay the fees needed to cover maintenance costs (Gulati et al 2005, Groenfeldt and Svendsen 2000).

In contrast to this top-down approach, there emerged in the 1970s a growing interest in farmer-managed irrigation systems. Coward (1980) drew together a series of articles reporting on successful community and bureaucratically operated systems in which farmer management and decision making played a major role. Other case studies and meta-analyses of irrigation systems with effective farmer management (e.g., Uphoff 1986, Ostrom 1992, Lam 1998) prompted policy attention to increasing the involvement of farmers in state-run systems (participatory irrigation management, or PIM), and even to programs of transferring management from the state to farmer groups (irrigation management transfer, or IMT).[1]

The most serious effort to introduce such reforms at a national level began in the Philippines in the late 1970s (Korten and Siy 1989). A very progressive group of managers in the National Irrigation Administration (NIA) worked with academics

[1] See Groenfeldt and Svendsen (2000) for a complete definition of these concepts.

and others representing a series of disciplines for more than a decade to “transform a bureaucracy.” The initial performance increases in the Philippines prompted the World Bank and the Asian Development Bank to promote greater farmer participation, and ultimately IMT as a means of improving the performance of government-managed irrigation systems. The development of water user associations (WUAs) to foster farmer participation became a conditionality for loans.

But even with international donor support, IMT has been largely unsuccessful, for a complex set of reasons (see Mollinga and Bolding 2004 and Mukherji and Facon 2009 for an assessment of the problems and potentials of PIM/IMT). As Oorthuizen (2003) notes, one needs to understand “the everyday politics of irrigation management and reform.” Importing institutions from one place to another, or from farmer-managed to government-managed systems, proved much more difficult than importing irrigation technologies. The Chinese experience with promoting water user associations and a range of village-level irrigation reforms ranging from collective activities to supervisory activities by the village head or a contracted manager is illustrative: the result has been an increase in water-use efficiency in a number of cases while yields and incomes have remained constant (Wang et al 2009). Given the variability of physical and socioeconomic conditions, Huang et al (2008) conclude: “In China’s future design of water management reforms, policy implementation should depend on local conditions of the villages and it should be recognized that not one reform path fits all villages.”

Closely linked to the concept of irrigation management transfer is “cost recovery.” How much should farmers be willing to pay for water? This includes both operation and maintenance (O&M) costs and the full cost of system construction. This decision is clouded by the issue of who benefits from irrigation investments. The main beneficiaries have been consumers, for example, in the form of lower rice prices. However, most analysts generally agree that farmers should pay the cost of O&M. The objective is to ensure viability of the funds needed to sustain the physical infrastructure (Molle and Berkoff 2007). Concerns regarding physical sustainability arose particularly in the 1980s when it was realized that many relatively new systems needed rehabilitation. Roughly speaking, cost recovery was accounting for only about 25% of O&M costs, of course, varying widely from one country and one system to another. The World Bank, by far the most constant and insistent advocate of cost recovery, observed in 2003 that there has been no evidence of better cost recovery or of covenant compliance over time (World Bank 2003). As noted above, the problem is compounded by the policies of the multilateral donors themselves, as countries know that when their irrigation systems deteriorate funds will always be available for rehabilitation.

Financial autonomy—total or partial—practiced through the development of strong farmers’ associations capable of sustaining the physical infrastructure and guiding other management practices has been achieved in Japan, Taiwan, and Republic of Korea. Furthermore, Small and Carruthers (199l) argue that the institutional arrangements for service fees whereby farmers’ fees go directly to irrigation agencies have been instrumental in increasing the performance of government systems in East

Asia. As noted above, China is making progress in this area. But this has yet to be achieved in most of the rest of Asia because of socioeconomic, political, and technical constraints.

Groundwater development and the expanding role of pumps

As with surface irrigation, groundwater development in Asia goes back millennia. However, until the advent of modern pumping technologies, the high costs of manually lifting water limited the use of groundwater for paddy cultivation to occasional supplemental use to fill in for gaps in rainfall or surface systems. The advancement in hydrogeology science and well construction also added to the explosion in groundwater use for irrigation. In discussing groundwater development, it is useful to distinguish two different situations: (1) the use of wells to tap deep aquifers as commonly found in India and Pakistan, and also for water supply for cities, and (2) the use of shallow low-lift pumps to tap shallow alluvial aquifers, which are usually replenished every year. However, as noted in the section "The expansion in irrigation since the 1960s," pumps are also used for surface irrigation and drainage (Barker and Molle 2004).

The pumps created a new environment for agriculture in Asia, giving farmers access to water on demand. In areas with active water markets, water became available to those farmers who could not afford pumps (Shah 2009). As rice prices fell, pumps were used to grow higher-value crops.

The spread of pumps occurred most extensively in the rice-growing deltas, for example, being used to grow a *boro* or dry-season crop in Bangladesh or, alternatively, to better manage the surface waters in the Mekong. Many of the pumps were located in surface irrigation command areas. In one sense, there would appear to be a complementarity between groundwater and surface water. For example, Dhawan (1989, 1993) notes that, in Indian Punjab and elsewhere, more than half of the water farmers pump from their wells is recycled canal water. Elsewhere, tanks have been a source of groundwater recharge. However, in many areas, recharge from surface sources has not kept pace with groundwater extraction, leading to widespread depletion of groundwater levels across large areas of India, Pakistan, and China.

Where aquifers are depleted (or if energy supplies become unreliable), groundwater also loses its advantage in terms of reliability of water supplies. Whereas in surface systems it is usually tail-enders that suffer, in the case of groundwater depletion, farmers near canals with good recharge or who have resources to keep deepening will suffer less than more distant or poorer farmers. Meinzen-Dick (1996) found that, in Pakistan, those who purchased water from other farmers, especially younger and smaller farmers, were more likely to be denied groundwater when they needed it.

Moreover, the advent of pumps created a distinct problem for the surface irrigation systems. In one sense, privately operated pumps led to the irrigation management transfer (IMT) that many have long sought (Shah 2009). In surface irrigation systems in the humid tropics, farmers in the tail end of the system, often denied adequate water, could purchase pumps. However, now farmers with pumps could "opt out" of cooperation in farmers' associations and helping to maintain surface systems. Because it has generally been the wealthier farmers who can purchase wells or keep them in operation as water tables fall, the loss of cooperation from these farmers has a particularly strong effect on collective surface management. Palanisami and Balasubramanian (1998) have shown that a higher density of wells is a contributing factor to the decline in irrigation tanks in southern India.

Again, the Chinese experience in managing groundwater seems instructive. In a recent survey of water management practices in China and India (Shah et al 2004), the authors observed in northern China a variety of contractual arrangements for managing tubewells at the village level with the contractors' responsibility including (1) operation and maintenance of the system, (2) orderly distribution of water to farmers, (3) collection of irrigation fees, and (4) payment of fees to the village electrician. However, the authors were quick to point out that the approaches China is trying are not necessarily appropriate for other countries and may not even solve China's problems.

Ecosystem services and environmental concerns

Although the main function of rice fields is to produce rice, they also provide a range of other "ecosystem services," which can be defined as positive externalities or nonmarket benefits of rice production (Millennium Ecosystem Assessment 2005, Boisvert and Chang 2006). Many of the ecosystem services are attributed to the presence of a surface-water layer of the paddy fields (Groenfeldt 2006, Masumoto 2005). The rice ecosystem provides types of food other than rice: raising fish and ducks in rice fields, canals, and ponds; frogs, snails, and rice-field weeds are collected as food in many countries. From a water management and hydrology point of view, rice fields provide very important *regulating services*. Bunded rice fields may increase the water storage capacity of catchments and river basins, provide groundwater recharge, lower the peak flow of rivers (Matsumoto et al 2004, Mitsuno et al 1982, Swallow et al 2002), and prevent or mitigate land subsidence, soil erosion, and landslides on sloping lands. Rice can be used as a desalinization crop because the continuously percolating water leaches salts from the topsoil (Bhumbla and Abrol 1978). Rice soils that are flooded for long periods of the year contribute to carbon (C) sequestration by taking CO_2 from the atmosphere (Bronson et al 1997, Dobermann et al 2003). Flooded rice land provides an important *supporting service* to the environment that has been classified as human-made wetlands by the Ramsar Convention on wetlands (Ramsar 2004). Rice landscapes sustain a rich biodiversity (flora, aquatic, birds; van der Weijden et al 2010) and also enhance biodiversity in urban and periurban areas (Fernando et al 2005). Rice affects daily life in many ways and the social concept of *rice culture* gives meaning to rice beyond its role as an item of production and consumption (Hamilton 2003).

Not all externalities of rice are positive. Since the beginning of the Green Revolution, there has been concern about the negative externalities or nonmarket impacts of irrigated agriculture. For example, the introduction of high-yielding varieties brought with it a sharp rise in the use of pesticides and chemical fertilizers as well as a loss of agro-biodiversity as high-yielding rice replaced other landraces or other crops, such as millets (Hossain et al 2007). The damage to not only the environment, to the production of rice and fish, but also to human and animal health is well documented (Rola 1987, Pingali and Roger 1995). As a reaction to these negative externalities, scientists have developed disease- and insect-resistant varieties, but, in addition, there has been and continues to be a concerted effort in many locations to encourage farmers to use less pesticide.

Ammonia-N emissions from lowland rice fields are estimated to be roughly 3.6 Tg per year, which is some 5–8% of the globally emitted ammonia-N per year (Kirk 2004). Volatilized ammonium can be deposited on the earth by rain, which can lead to water pollution, soil acidification (Kirk 2004), and unintended N inputs into natural ecosystems. Water pollution can also be caused by the direct flow of dissolved nitrogen through runoff and seepage water. High nitrogen pollution of surface fresh waters can be found in rice-growing regions where fertilizer rates are excessively high, such as in Jiangsu Province in China (Cui et al 2000). Contamination of groundwater may arise from the leaching of nitrate or biocides and their residues (Bouman et al 2002). Nitrate leaching from flooded rice fields is quite negligible because of rapid denitrification under anaerobic conditions (Bouman et al 2002, Gumtang et al 1999). However, nitrate pollution of groundwater under rice-based cropping systems surpassed the 10 mg L^{-1} limit for safe drinking water only when highly fertilized upland crops were included in the cropping system (Gumtang et al 1999, Bouman et al 2002). Little is known about the residue of biocides used in rice production, and their toxicity.

The spread of rice irrigation by groundwater has brought new water problems. High levels of arsenic (As) in groundwater have been reported in Bangladesh and in other Asian deltas (Ng et al 2003). Irrigation with As-contaminated groundwater causes As accumulation in the topsoils, which is taken up by the plants. Though the As uptake resides mostly in root and shoot tissues, with very little As translocated to the grains, the effect of As on the food chain (including animal meat and milk) needs further study because human health is of major concern. Another critical issue of As contamination is sustainability. High As concentration in the soil has been reported to cause a grain yield reduction (Jahiruddin et al 2004), but, in general, our understanding of the (long-term) behavior of As in agriculture is too limited to assess the risks.

With the present concerns on global climate change, greenhouse gas (GHG) emissions from rice fields receive much attention. Irrigated rice systems are a significant source of methane (CH_4) and a small source of nitrous oxide (N_2O). In the early 1980s, it was estimated that lowland rice fields emitted about 10–20% of the then-estimated global methane emissions (Kirk 2004). Current estimates are in the range of 20 to 60 Tg, being 3–10% of total global emissions of about 600 Tg (Kirk 2004). Few accurate assessments have been made of emissions of nitrous oxide from rice fields, but it is generally agreed that, in irrigated rice systems with good water control, nitrous oxide emissions are quite small except when excessively high fertilizer-N rates are applied.

GHG emissions also come from water pumping. Other environmental impacts would include waterlogging/salinity from poorly drained surface systems, and falling water tables from overpumping.

In summary, depending on environmental conditions and how rice fields are managed, rice fields can have a positive (ecosystem services) or negative (environmental pollution) impact on the environment. Since rice has been part of society and the landscape for generations, most of the ecosystem services have been taken for granted. It is important to recognize, quantify, and value them properly and to supply adequate incentives to farmers to enhance these ecosystem services, for example, in the form of "payment for ecosystem services."

Most of the negative impacts of rice fields are caused by overuse or misuse of chemical inputs (fertilizers and biocides). Although plenty of scientific evidence indicates that these can be reduced greatly, most rice-growing countries lack institutional setups to monitor or regulate inputs used by farmers. In fact, quite the opposite, many governments are inclined to subsidize chemical inputs with the often-mistaken notion that this will increase rice production.

From development to management of water resources

The emphasis in the past several decades has been on the development of water resources, both surface water and groundwater. Relatively little attention has been paid to management. We have now reached a point at which opportunities for further development are extremely limited and costly. Failure to manage groundwater aquifers has led to overextraction in many areas. Furthermore, demand is growing for water for nonagricultural purposes, such as hydropower, urban consumption, and industry. In this section, we focus on different aspects of the management problem.

The future of gravity-flow irrigation

With wide-ranging changes that have swept through Asian agriculture during recent decades, new questions have arisen about the future of gravity-flow irrigation that has dominated Asia's irrigation for millennia. Flow irrigation technology satisfied precolonial and colonial states, which viewed canal irrigation as a way to combine "interests of charity with interests of commerce" (Whitcombe 1971). Other conditions helped, too. Feudal agrarian institutions helped control anarchy in irrigation systems and secure forced labor for regular cleaning of channels at little cost to authorities. Irrigated agriculture was dominated by wet-season rice paddies, which made water distribution relatively simple. Lifting water—which provides an alternative to gravity-flow irrigation today—was laborious; transporting it in open channels over undulating terrain was difficult. All this helped forge self-managing "irrigation communities," supported and sustained by the elaborate revenue apparatus of the state that lived off the land (Shah 2009).

All these conditions have changed or disappeared during the past 50 years. Land revenue has become insignificant as a source of government income; as a result, revenue administration has disappeared or weakened in most Asian countries (except for Central Asia, where the state still lives off the land). Farmers are no longer content with just a single crop of wet-season rice; throughout Asia, farmers are striving for a dry-season rice crop or to diversify to other high-value crops for markets. Rising population pressure is generating pressure to intensify farming; growing urban demand is generating pressure to diversify to high-value crops. Cheap pumps and boreholes offering on-demand irrigation have helped farmers to intensify and diversify their farming systems. But, the options of individual water use have also allowed people to opt out of the coordination institutions required when people share water (as described below). The rise of the atomistic groundwater economy thus poses a serious threat to the millennia-old surface irrigation model.

The stagnation and decline in canal irrigation are often blamed on unaccountable or inefficient irrigation bureaucracies. This may certainly have a role, but the larger truth is that many of the socio-technical preconditions that made gravity-flow irrigation sustainable in the past no longer exist. New conditions that have taken their place demand a new business model for gravity-flow irrigation that is nowhere to be seen.

Irrigation management transfer and participatory irrigation management have been tried, for some decades now, as just such a new irrigation business model. However, barring a few "islands of excellence," IMT and PIM do not fill the bill as a workable model for surface irrigation systems on a large scale. The challenge is to provide a workable alternative.

In South Asia, large and small surface systems are losing their traditional role of gravity-flow irrigation and becoming important more as aquifer recharge systems supporting the groundwater economy. In the Indian Punjab, with a dense network of irrigation canals, most irrigation occurred by gravity flow in the 1960s; today, tubewells serve more than three-fourths of the irrigated area.

Elsewhere, at the periphery of irrigation command areas, on-demand lift irrigation from the canal network is growing in importance compared with gravity flow. In the famous Narmada project in western India, lift irrigation has become the dominant mode of irrigation as farmers refuse to part with their already scarce land for construction of the distribution network. The government is unable to make much headway with the construction of distribution canals. But, farmers bought 70,000 diesel pumps in 3 years to start pumping water from canals (Shah 2009).

Many government and donor functionaries are yet to come to terms with these "design modifications" made by farming communities and keep treating these as "irregularities" in need of correction. But, such modifications are occurring on such a large scale and so rapidly that the design concept of surface irrigation itself may need rethinking.

A conference on the future of large rice-based irrigation systems in Southeast Asia (FAO 2007) reached the following conclusions, which would apply to South Asia as well:

- Modernization of irrigation systems and their management to increase their flexibility and insert them into river basin management, while taking into account the multiple functions of agricultural water management, is more needed than ever.
- To respond to the complexities, management needs to be made more professional and present institutional reform models need to be evaluated and overhauled to respond to new demands and characteristics of farmers.

Finally, yet another element affecting the management of gravity-flow irrigation systems is the large number of dams being constructed for hydropower in the upper reaches of the rivers of the Himalayan watershed (as described by Molle et al 2009). In most countries, we find separate agencies dealing with hydropower, irrigation, and the environment that do not communicate with each other.

The conjunctive management of rainwater, surface water, and groundwater

The concept of water management must have at its center new strategies for conjunctive management of rainfall, surface storages, and groundwater resources. In many parts of Asia, conjunctive use of these three by farmers is already widespread. But, this is more by default than by design. The simple first step to conjunctive management—changing the operating rules of reservoirs and main systems—itself is yet to be taken, let alone more refined ideas of conjunctive management. In many parts of monsoon Asia, using floodwaters of seasonal rainfall for systematic groundwater recharge makes eminent sense today but has so far failed to attract policymakers' attention or resources. Depleted aquifers are bemoaned, but these can also be viewed as potential storages. Yet, in South Asia, using aquifers as storages offers big opportunities today that were not available in the 1960s and earlier. Government and donor priorities still favor the construction of new surface storages.

Massive investments being planned for rehabilitating, modernizing, and extending gravity-flow irrigation from large and small reservoirs need rethinking in those areas where groundwater has emerged as the mainstay of smallholder agriculture. The current orthodoxy is that South Asia needs more reservoir storage because it has only 262 m^3 per capita compared with 6,103 m^3 in Russia, 3,145 m^3 in Brazil, 1,964 m^3 in the United States, 1,111 m^3 in China, and 753 m^3 in South Africa (Malik 2007). This is an inappropriate cross-country comparison, for it fails to answer why India, with among the world's smallest per capita storage, has one of the world's largest irrigation areas.

Over the past 40 years, the South Asian landmass has been turned into a huge underground reservoir, more productive, efficient, and valuable to farmers than surface reservoirs. For millennia, it could capture and store little rainwater because in its predevelopment phase it had little unused storage. The pump irrigation revolution has created 285 to 300 km^3 of new, more efficient storage in the subcontinent. Like surface reservoirs, this is good in some places and not so good in others. To the farmers, this reservoir is more valuable than surface reservoirs because they have direct access to it and can scavenge water on demand. Therefore, they are far more likely to collaborate in managing this reservoir if it responds to their recharge pull. Indeed, farmers would engage in participatory management of a canal if it served their recharge pull, as illustrated by the emergence of strong canal water user associations of grape growers in the Vaghad system in Nasik District of Maharashtra. These farmers undertake proactive canal management here mostly because they value canals as the prime source of recharging the groundwater that sustains their high-value orchards (Bassi 2006, personal communication).

In areas of South Asia with massive evaporation losses from reservoirs and canals but high rates of infiltration and percolation, the big hope for surface irrigation systems—small and large—may be to reinvent them to enhance and stabilize scavengeable water supply close to points of use, permitting frequent and flexible just-in-time irrigation of diverse crops. Already, many canal irrigation systems create value not through flow irrigation but by supporting well irrigation. In the Mahi Right Bank System in Gujarat in India, with a command area of about 250,000 ha, it is the more than 30,000 private tubewells—each complete with heavy-duty motors and buried pipe networks to service 30 to 50 ha—that really irrigate crops; the canals merely recharge the aquifers.[2] An elaborate study by Shah (2009) lauded the Mahi irrigation system as a "model conjunctive use project" in which 65% of water was delivered by canals and 35% was contributed by groundwater wells. However, what conjunctive use was occurring was more by default than by design: the then-chairman of the board wrote in the preface (ii): "The credit … [goes to] the enterprising farming community of the area who have taken the initiative and who realize fully the advantages of adopting the conjunctive use techniques for reaping optimal benefits." In a study of conjunctive use in the Mahi system, it had been argued that, while farmers were doing their bit, the management of the system itself was totally antithetical to optimal system-wide conjunctive management of rainfall, surface systems, and groundwater wells (Shah 1993, p 176-201). Here and elsewhere in Asia, conjunctive management has yet to be realized.

Improved demand management

A key area of concern through much of Asia—indeed, in much of the developing world—is the demand-side management of the irrigation economy. Pricing of irrigation water everywhere is neither effective in full cost recovery nor in signaling scarcity value of water nor in directing scarce water to higher-value uses. In informal irrigation, such as from groundwater and lift irrigation from rivers, channels, and tanks, transaction costs of pricing are high. But, even government irrigation systems in much of Asia have failed to use pricing as an effective demand management tool.

In many parts of the New World, water rights and entitlements have been used with some success in improving water productivity and demand management. In the western U.S. and Australia, the emergence of a variety of water rights systems has been an outcome of a long evolutionary process of the society as a whole. However, in countries such as Chile and Mexico, a new system of entitlements has been created through legislative changes. The impacts have been variable. But, similar strategies have been advocated in the developing world, including in Asia, as part of integrated water resource management (IWRM) during recent years. Countries such as Sri Lanka, Thailand, Indonesia, Malaysia, and Nepal have enacted IWRM laws and enunciated this in national water policies. Evidence so far suggests, however, that creating rights and entitlements by legal fiat has largely come unstuck.

[2]Dhawan and Satya Sai (1988) showed for Mula command and then for Punjab that the indirect benefits of canal irrigation from groundwater recharge far exceed the direct benefits of flow irrigation.

Demand management is proving particularly challenging in groundwater. For example, India and Pakistan have made laws to regulate groundwater overdevelopment. In India, the Supreme Court heard a Public Interest Litigation appeal, and ordered the creation of a National Groundwater Authority mandated to bring unregulated groundwater overexploitation to a stop forthwith. This was in 1996; but, in the 12 ensuing years, the result has been nil. Governments are discovering that it is easy to make groundwater laws, but difficult to enforce them.

Groundwater irrigators have also emerged as important "vote banks" in South Asia that politicians find hard to ignore. Especially in India, the present groundwater boom was not only catalyzed by government policies but is today sustained by government subsidies to farm power supply. The challenge is not only protecting the resource and saving livelihoods of the poor but also preventing the power industry from bankruptcy. Gujarat recently separated electricity feeders supplying farm power from the rest of the rural grid and began rationing the power supply to tubewells in an effort to contain farm power subsidies. As a collateral effect, it has also been able to cap groundwater withdrawals. The results have been so satisfactory that other Indian states such as Punjab and Andhra Pradesh have followed suit.

With millions of small farmers, Asian countries will likely have to invent such indirect methods of water demand management rather than using pricing, entitlements, or laws. Getting incentives right for shifting water-intensive crops (including rice) to water-abundant basins and water-economizing crops to water-stressed basins can be one means of demand management.

Managing water scarcity

Water scarcity is a real issue facing agricultural water management. In addition to the drivers of population growth and increasing demands from various competing sectors, degrading water quality and mismanagement have created water scarcity within many basins and scheme areas. There is an urgent need to save water and to increase water productivity (WP), that is, the amount of rice produced per one unit of water used (Tuong et al 2005), at different scales, from field to system and to basin level.

Tuong et al (2005) derived five principles for reducing the amount of irrigation water to input in rice production. They include increasing grain yield per unit water transpired, effective use of rainfall and water stored in the field or system, and reducing nonbeneficial depletion (evaporation, E) and outflows (seepage and percolation, S&P). Field-level practices to reduce S&P include

(i) Saturated soil culture (SSC), in which the soil is kept as close to saturation as possible without maintaining standing water. Water input can be decreased from 5% to 50% with no yield reduction.

(ii) Alternate wetting and drying (AWD), in which irrigation is applied to obtain 2 to 5 cm of field water depth. Then, after a certain number of days (normally 2–7), when the field has dried out, water is applied again. Water input can be reduced by 15–30% with no loss in yield.

(iii) Aerobic rice is a practice that can be followed where there is severe water scarcity and inadequate water to grow flooded rice. Rice is grown as an irrigated upland crop on nonpuddled soil. But, aerobic conditions have a high yield penalty over lowland rice. Research is under way to develop varieties suited for aerobic conditions.

Adoption of the first two methods above requires a high degree of water control. This is not much of a problem for farmers using their own pumps, but it is for farmers in large-scale surface irrigation systems that lack flexibility in, and reliability of, water delivery. It is also a problem for farmers using electricity to pump groundwater where supplies are unreliable, as in northwest India. Mistiming of irrigations results in low WP with respect to irrigation water (Smith et al 1985) and, if a water deficit occurs at crop anthesis (flowering), WP with respect to transpiration will also decrease. The timeliness and reliability of water delivery require good irrigation system delivery infrastructure and operation schemes. For large irrigation systems with considerable lag time between diversion of water at the source (river or reservoir) and its arrival at the farmer's gate, it is almost impossible to match system delivery and field-level demand, especially when a part of the crop water requirement is met from rainfall. In some parts of China, this difficulty is avoided via two-level management: the supply-driven main system is managed by irrigation system managers, while farmers have control over the timing and amount of water at the farm gate via small farm ponds that store water to regulate the irregularity of the main system (Mushtaq et al 2006). In Taiwan, ponds are integral parts of an irrigation system, aiming at improving farmers' control over the timing and reliability of the water supply. Such controls at the tertiary canals or turnout level facilitate farmers' field water-saving technologies by ensuring that water is available when it is needed.

Farmers will adopt water-saving technologies when they have incentives to do so. This is the case when they have to pay for their irrigation, for example, pumping from groundwater or from canals: saving irrigation water means saving money. In large canal irrigation systems, the "incentives" can come from enforced regulation, rationing (Loeve et al 2004), price incentives (Molle and Berkhoff 2007), and voluntary water markets. However, there are often difficulties in making such incentives operational. For example, water pricing is not likely to provide an incentive in surface systems unless it is combined with volumetric measurement and suitable institutional setups such as water rights and the technology to transfer water from one place to another. In short, for farmers to profit from water-saving technologies, this may require both infrastructural and institutional changes.

Water savings at the field level may not necessarily lead to water savings at a larger scale (e.g., system, basin level). Most of the outflows from the field go into drainage canals or recharge aquifers. In many cases, the outflows from the field are re-captured and reused downstream through pumping from creeks, drains, or shallow groundwater (Zulu et al 1996, Hafeez 2003). Because of the existing recycling and conjunctive use of water in many rice areas, the amount of water that can be saved at the system level could be far less than assumed from computations of field-level water savings. The effective recycling of drainage water and conjunctive use of groundwater also pose a question whether we should apply technologies such as SSC, AWD, and aerobic rice to reduce field-level outflows or investment should be made in recycling outflows. The choice obviously depends on the relative cost-effectiveness of the strategies.

Transferring water from agriculture to nonagricultural uses

As we look at the future, what is abundantly clear is that there will be less water for agriculture as pressure increases to meet urban and industrial demand and greater recognition of the needs of the environment. Water transfer from one user to another is a long-standing practice. We note, for example, the water markets that have sprung up in association with low-lift pumps. Transfers between sectors are a more recent phenomenon (Lund et al 1992). The pressures to transfer water are being increasingly felt in Asia.

The characteristics of water transfer in a specific location are dependent on a wide variety of factors—physical, economic, social, and political (Levine et al 2007). In deciding on the appropriate transfer, three basic questions arise:

- For the conditions that exist, which type of transfer mechanism is most appropriate?
- How can equity in the transfer be assured?
- How can third-party interests be considered?

Assuming that water can be physically transferred, water transfers can be characterized by the nature of the transaction and by their time duration. For the former, the transfer can occur as a result of market forces or mandated. *Water markets* are said to be the most economically efficient allocation of water resources (Fredrick 1998, Simpson 1994), but, for water markets to function efficiently, there must be, in addition to willing buyers and sellers, a reasonably competitive environment, including a relative balance of power between the buyers and sellers. Where the conditions for a true water market do not exist, modifications can be made to address the deficiencies and retain the market orientation. The water banks in California illustrate this type of quasi-water market. Fundamental to a market-oriented approach to water transfer is secure water rights, and, in most Asian countries (in fact, in most developing countries), these do not exist. Thus, most water transfers in Asia result by fiat, usually ordered by the government.

The time duration of a mandated water transfer is important because of its implications for the nature and amount of compensation that might reasonably be provided for the transfer. Compensation can vary widely in amount and take many forms. If the transfer is short-term, the adverse impact can be relatively minor and the transaction costs associated with compensation relatively high, and a failure to provide compensation may be justified. However, if the transfer is of longer duration, compensation often will be expected (Levine et al 2007). When the compensation approach is to minimize the adverse impact on irrigators, monetary payments may be made directly to the irrigation association (often the primary user of the water) to provide resources for system improvement (Chemonics 2005). However, if the irrigators experience crop loss, they may receive direct payments in compensation or there may be reliance on indirect methods of compensation, including tax relief, crop subsidies, and education on improved irrigation and cropping practices, etc.

The conditions that would lead to a specific type of transfer mode are illustrated in Figure 3.

Some examples of water transfer and compensation are cited below (see Barker and Giordano 2007). In each case, it should be noted that the infrastructure needed to make the water transfer is in place:

- Hyderabad, India (Celio and Giordano 2007). To protect the water supply of Hyderabad, rules govern the release of water for irrigation. Although in general the urban water supply received priority over agricultural production, evidence suggests that, in cases of severe drought, agriculture came first for political reasons. Although there has been much discussion about compensation, farmers have received no compensation to date.
- Tone River Basin, Japan (Matsuno et al 2007). With rehabilitation and the establishment of pipelines, farmers gave up water rights but received an indirect benefit with reduced labor requirements for irrigation. No loss in rice production occurred.
- Chang-Hwa and Yun-lin Irrigation Associations in Taiwan (Huang CC et al 2007). Strong demand for water for a petrochemical plant led to water transfer and compensation decided by negotiation and finally government arbitration. Compensation was paid to irrigation associations that held the water rights and not to farmers.

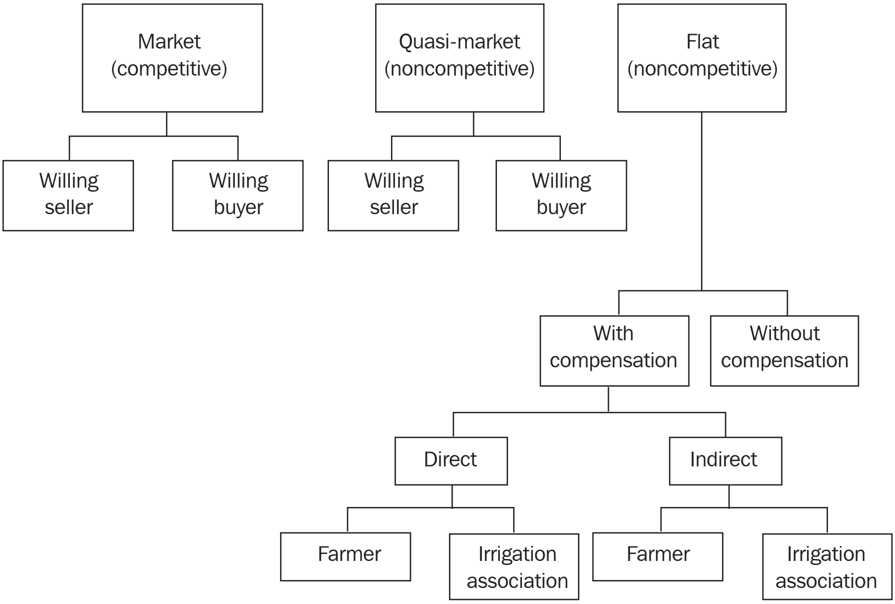

Fig. 3. Water transfer characteristic modes. Drawn by Gilbert Levine.

- Zhanghe Irrigation System in Hubei, China (Loeve et al 2007). In the 1960s, 80% of the water from the Zhanghe reservoir was allocated to agriculture, while today it is about 20%, with little loss in rice production. Water savings at the farm level have been due to several steps, including volumetric pricing of water to villages in the 1980s, the adoption of alternate wetting and drying, and the rehabilitation and construction of farm ponds (noted earlier). The water transfer has been by fiat (Fig. 3), but indirect compensation has been directed to farmers in the form of training in AWD practices, and more recently a reduction in taxes and subsidies on the basis of area planted to rice.

In summary, demand will be steadily increasing for water from the nonagricultural sectors. Agriculture must find ways to maintain or increase production by increasing water productivity. At the same time, equitable transfer requires that farmers receive some form of compensation. This, in turn, requires at least implicit recognition of farmers' water rights, as discussed below.

Institutions, organizations, and water access

Experience with the past 50 years of irrigation has shown that technology alone is not sufficient to reduce poverty, enhance food security, and increase rural livelihoods. In many cases, the technologies were not adopted or maintained, or the poor, women, and other marginalized groups were excluded from the benefits of technologies. Appropriate institutions are necessary for technologies to fulfill their intended roles.

Institutional arrangements

Figure 4 illustrates the importance of two types of key institutions for irrigation. The vertical axis illustrates the spatial scale of a technology, from an individual plot, through a whole farm, to one that covers several farms, and a village, to a region. All approaches that are above the scale of the individual farm require some form of coordination—by local organizations, the state, or the market. For example, a drip kit may be adopted by an individual small farmer, and a tubewell may serve just one farm, but where holdings are very small and tubewells have large capacity, farmers may join together to buy and operate a tubewell, or the state may install and operate it, or one farmer can install it and sell water to neighbors. How well each of those institutions functions will determine whether smallholders receive adequate and timely water supplies. Even if a drip kit can be operated independently by one farm household, access to the kit within a farm household will matter, and, depending on the water source or the return flow, other farms might be affected and collective institutions come into play.

The horizontal axis in the figure indicates the permanence of a technology or approach, or the time frame to cover the investment. The longer the temporal scale, the greater the need for property rights to provide authorization and incentive to make the investment. Even a tenant or a wife without independent land rights can install a

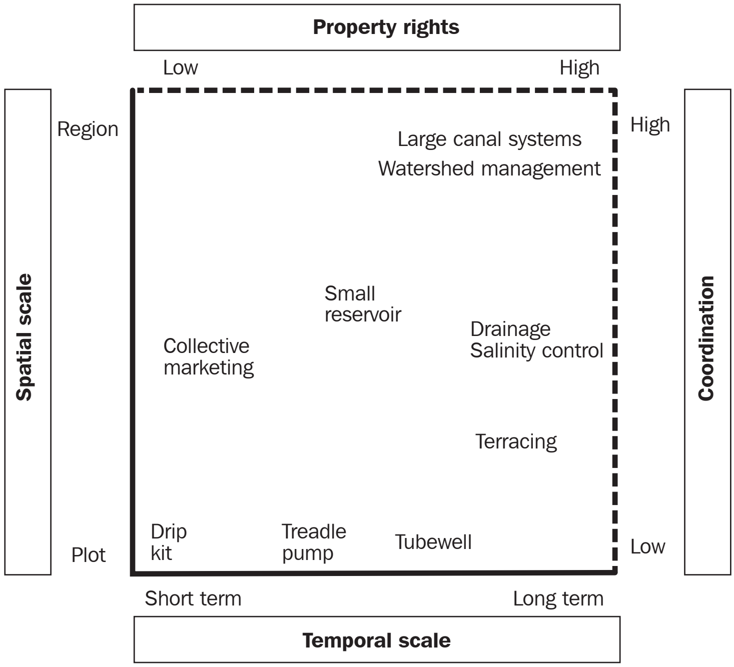

Fig. 4. Institutions for agricultural water management. Source: Adapted from Meinzen-Dick et al (2002).

drip kit, but may not be allowed to install a treadle pump or tubewell, and may not have the incentive to install and maintain terracing or drainage systems for salinity control. Even if farmers have secure rights to the land, they may not be willing to invest in irrigation systems if they do not also have secure rights to the water. This has been the problem with many irrigation management transfer systems, in which farmers were expected to bear the costs, without secure rights to the water from the systems.

Although the exact location in this figure would depend on the size of the farms and the scale, as well as the cost/return ratio, of the particular technology, this provides a useful starting point to ask about which institutions are likely to be critical.

Identifying the important institutions is relatively easy compared with ensuring that these are in place. Analogies of "social engineering" have been misplaced, because they imply a mechanistic approach (Mollinga et al 2007). Rather, institutions are organic and path-dependent—they cannot simply be imported from one context to another. This requires a more nuanced approach, which may require mutual adaptation of the physical and institutional environment. Failure to recognize this lies behind many of the apparent failures of programs such as irrigation management transfer.

Coordination institutions

The need for water users to work together has been apparent for millennia in Asia, especially where farm sizes are small relative to the size of the irrigation systems. The farmer-managed irrigation systems of Indonesia (Bali), Nepal, or India, for example, have worked out arrangements to mobilize the labor and other resources needed to build or maintain the systems and to share the water among themselves. In larger systems, it was often the state that provided the coordination—mobilizing resources to build, operate, and maintain the systems.

As water use increases, the separation between users decreases and one person's water use affects another's (Bruns and Meinzen-Dick 2000). Unless there is coordination, the result is often negative externalities, whereby the quantity or quality of water available to one user is depleted by the other. This is most notably seen in the rapid depletion of aquifers, especially in India and China, because thousands of farmers with individual wells and mechanized pumps operate without effective regulation by the state or coordination among neighboring water users. Increasing pollution loads from agrochemicals, industrial effluents, and municipal sewage have overloaded the natural cleaning capacity of many ecosystems.

The example of the tubewell cited above illustrates that coordination functions can be provided by the state (a public tubewell that supplies many farms), collective action (a farmer group), or markets (a farmer selling water). Which institution is most appropriate depends on the particular conditions—for example, scale, technical sophistication of the technology and the farmers, and cultural factors (social capital, market orientation). In general, the advantages of the state are greatest at the largest scale; collective action at more localized levels and markets are highly variable in whether they provide effective coordination among smallholders.

Much literature addresses the factors that are likely to affect the performance of public, collective, and market-oriented irrigation institutions (see Coward 1980, Small and Carruthers 1991, Wade 1997 on public institutions; Ostrom 1992, Bardhan 1993, Meinzen-Dick et al 1997 on collective action). These relate, broadly, to the conditions of the resource itself, the nature of the user group (especially its human and social capital), and the rules governing the organizations as well as the water resources. Although a full review of these factors is beyond the scope of this article, two are particularly relevant in terms of the increasing challenges to irrigation systems today.

The first relates to the resource. Ostrom's (1992) seminal work identified the importance of clearly defined boundaries, monitoring, and sanctioning as crucial for long-enduring irrigation institutions. These are relatively easy to meet in surface irrigation systems, in which the irrigated area and quantity of water flows are relatively easy to observe. But they are much more difficult for aquifers and water quality management. Because groundwater quantities are difficult to observe and measure, and it is difficult to predict how one person's use affects others, there are very few examples of effective groundwater management worldwide. Most water measures also focus on quantity, not quality, which is more difficult to observe. These are among the reasons that depletion of groundwater and water quality has gone unchecked for so long.

The second factor relates to the water users. If they know each other well through repeated interactions, both in the irrigation system and outside, they are more likely to cooperate. But, as the number of transients increases due to migration and occupational mobility, it becomes more difficult to establish cooperation.

If group-based approaches are selected for water management or technology dissemination, it is important to look beyond the formal rules and membership roles to see whether the group is actually acting collectively and who is included and excluded from active membership and decision-making. This means asking about women as well as men, landowners and tenants, farmers, and other water users (e.g., fishers, livestock keepers, home gardens, domestic users, other enterprises). There may be formal as well as informal barriers to participation, different motivations, and returns to be considered. There are indications that organizations with active participation of men and women may be more effective in managing resources like water because they draw upon the skills and resources of both, but the costs of establishing active mixed organizations are also greater than with single-sex organizations, especially where gender segregation is high in the society. All of these factors should be considered when identifying which groups to work with, particularly if that organization will gain stronger control over technology or water itself. Furthermore, just setting up the organizations is not enough for sustainability: they also need to become internalized and "institutionalized." Traditions of managing water are not necessarily transferrable to other places where irrigation or irrigation system reforms are being introduced. There is often a need to develop the skills and coordination. This is one of the major problems that have plagued irrigation management transfer programs.

This analysis helps to understand the situation with groundwater irrigation. Most surface systems serve multiple farmers and therefore require coordination for systems to work. Although state coordination institutions have performed relatively well in East Asia (where they have been accountable to the farmers), government irrigation agencies have not been as effective in much of South and Southeast Asia, leading to performance problems, One reason that groundwater or pump irrigation has taken off so quickly is that the pumps often serve a single farm, and therefore require less coordination, at least initially. But, as users increase, the interaction at the aquifer level becomes increasingly important, and there is a need for coordination institutions for the aquifer. Informal markets allow for sharing among neighboring farms, but do not coordinate over larger areas. At the aquifer level, there is very little boundedness of the group and low observability of the investment, creating even greater difficulty for aquifers than for surface irrigation units, especially in Asia.

Water rights and access

Ribot and Peluso (2003) distinguish between *access* to resources (e.g., being physically able to get water) and *rights* (entitlements). A tail-end farmer may have a right to water, but might not be able to get access because those upstream take too much. A farmer may also have access due to physical location, force, or even stealth, even if he or she does not have a right to the water. Many poor people do not have formalized rights to the water they depend on for their livelihoods. Strengthening their rights, which may involve getting the government to recognize them as legitimate claimants, will help increase their security and provide incentives for investments—even if very small—in agriculture.

Although there are enormous variations in water rights, even within Asia, several aspects of water rights are especially pertinent to rice irrigation, and especially to incentives for water conservation in rice. First, the vast majority of agricultural water rights in Asia are use rights that are often tied to particular pieces of land, and may even be specific to rice cultivation in a particular season. This type of water right creates very little incentive to save water, and may even create incentives to continue rice cultivation because those who do not exercise their water rights can lose them. However, if the rights are rationed, as in a *warabandi* (rotational irrigation system), there may be an incentive to conserve. Transferable water rights may provide even greater incentives to conserve water in rice cultivation, if the savings can be sold or leased to another water user. These are found not just in formal water rights systems (e.g., Australia), but also in some farmer-managed systems with water shares (e.g., in some systems in Nepal or Bali). However, transferable water rights require a mechanism with which the original user can refuse water and can transfer it to other users. Some recognition of farmers' water rights is needed to ensure compensation in the case of voluntary or forced water transfers discussed above.

But just passing laws and regulations will not necessarily change water rights. Water rights do not derive only from government law. A wide range of customary law and practices, religious law and interpretations, and project regulations also relate to water rights, and people may base their claims on any of these (Benda-Beckmann et al 1997). The definitions of water rights are becoming more complex with increasing competition for water and diversification of water uses.

A better approach is to start with people's experiences with water—how they access it, and what claims they make for their different water uses (see Table 1). This will help to identify the relevant legal frameworks to address. Then, an intervention can work to strengthen the claims of poor people for their important water uses. In many cases, water rights become operationalized through organizations. Ensuring that women, smallholders, livestock keepers, or other poor and marginalized water users are represented in those organizations is an important step to strengthening their water rights.

Thus, it is time to move beyond panaceas, including specific technologies or specific institutions and organizations. Rather, we need a range of options and the understanding to be able to tailor them to the physical and institutional context.

Assessing management options

Notwithstanding the lack of a panacea for improvements in agricultural water productivity, and the obvious complexity of the factors affecting that productivity, the foreseeable needs for increasing the utility of limited water resources are such that those improvements must be made. Research and experience suggest steps to take in the search for appropriate answers.

Before suggesting specific steps, two basic premises should be recognized. First, although we have focused on irrigation improvement, given its importance in agricultural productivity and the magnitude of its share of water use, it is necessary to recognize that any change in the way water is used in irrigation has implications for the entire watershed. Second, it should be clear that, regardless of the specific nature of the irrigation situation, management of the water resource is a shared responsibility of the government[3] and the users.

The first premise implies that there must be sufficient information about the watershed to assess any implications, but, as importantly, it suggests that the characteristics of the watershed—physical, social, economic, and political—should be considered as plans are developed, not after most of the decisions have been made. There are a number of examples of watersheds in which there are systematic, ongoing programs of information collection that are intended to provide a base for decisions about the use of the water resources. Examples are the Mekong River, where the Mekong Secretariat has been collecting such data to guide multinational development along the river, and the Lerma-Chapala River Basin in Mexico, where the information was used to develop a multistate basin plan, and continues to collect information as the plan is implemented.

The second premise recognizes that, whether the situation is control and allocation of surface water, prevention of overuse of groundwater, or conjunctive management of the two, both the government and users have important roles to play in any effort to increase water productivity sustainably. Two basic questions are inherent in this recognition—where in the process of managing the water resource does the transfer of responsibility occur, and to what extent is that management *administrative* or *managerial*?[4]

With these in mind, we can suggest an approach that poses a series of questions, the answers to which lead to different patterns of sharing and modes of implementing sustainability policies. Figure 5 illustrates the process for irrigation dependent upon groundwater.

In almost all countries, groundwater is a common-access resource. Even when the government has nominal "ownership," the difficulties of control of individual access are such that effective control by government alone rarely occurs, and then only when there is an explicit policy for sustainable groundwater development. In managing groundwater, the transfer of responsibility often occurs at the level of the user, but may take place at a higher level, depending upon the potential for cooperation among users.

The questions presented in the flow chart have imbedded in them questions that require significant knowledge of the local situation. For example, the question "Is there *equity in access?*" implies the need to define what constitutes equity in the specific

[3]Government in this case refers to the relevant authority that has jurisdiction of the water resource of concern; it may be local, state or province, nation, or, in a few cases, a multigoverning body.

[4]It is convenient to identify as *administrative* the application of predetermined policies and practices, essentially without reference to the situation in the field, and as *managerial* those practices that are responsive to the conditions in the field.

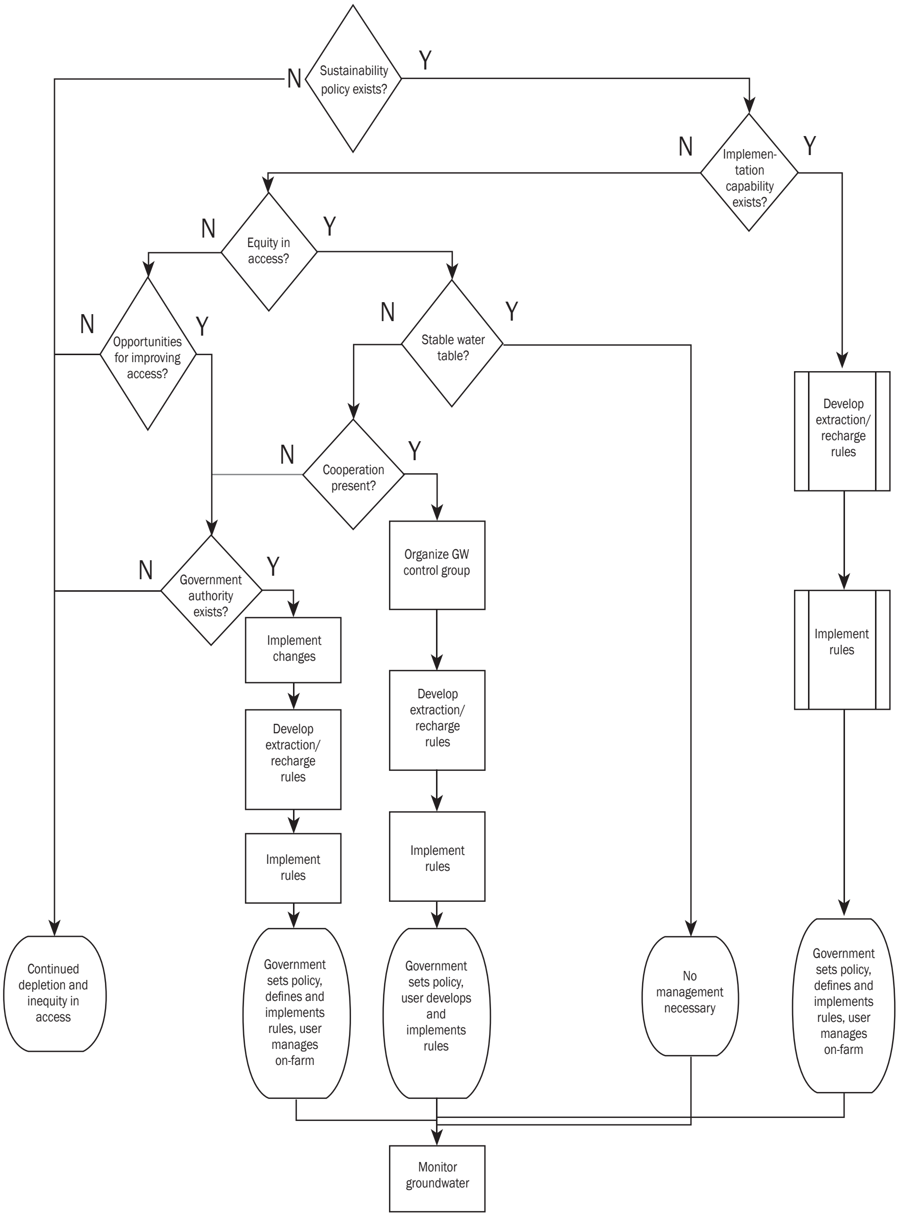

Fig. 5. Groundwater management options. Drawn by Gilbert Levine.

case. Does it mean equality of access (limits on size of pumping unit)? Does it mean a bias toward a specific group? Similarly, the question "Is *cooperation present?*" has embedded in it, What type of cooperation is needed for groundwater management? How to gauge the degree of cooperation that could be developed? The chart does not say anything about how the types of extraction/recharge rules might be formulated. These might include direct attempts to control extraction, for example, the issuance of extraction concessions coupled with the ability to monitor electricity at the pump level, as in Mexico,[5] or indirect attempts, through the pricing of energy.

Similar charts can be used to identify the options for administration/management of the water resource in the contexts of surface-water irrigation and conjunctive management of both surface water and groundwater. There will be more questions and a larger number of options, but the same basic issues exist—what are the basic objectives of a water policy? Where does responsibility (and authority) transfer from the government to the user (individually or in groups)? What are the appropriate rules to implement the policy? From a development perspective, there is one other important question in attempting to define action: To what extent should decisions be based upon *probabilities* or *possibilities?* Examples are numerous in irrigation development when decisions have been made that reflected *possible* outcomes, but when the reality of constraints, particularly in the socio-political realm, produced very different results.

Conclusions

The issues related to the use of water resources are many and varied. In Asia, the decreasing availability of water for irrigation has particular relevance for rice production. The combination of increasing competition from municipal and industrial sources, the overexploitation of groundwater, and the increasing costs of new source development point to a reduction in the availability of water for irrigation in much of the region. It is clear that there is a need for four concurrent efforts.

First, to slow down the rate of diversion of water from irrigation, efforts should be concerted on the watershed scale, to identify and reduce nonbeneficial water losses. Evaporation from nonproductive areas (recognizing that noncommodity environmental outputs are productive) and pollution that reduces the utility of the water are two major sources of these losses.

Second, to improve the overall management of the water resource, monitoring of the water sources and distribution should be improved. In many situations, this will require improved institutional arrangements as well as increased investment in physical infrastructure.

Third, to improve the utility of the water delivered through irrigation systems, in many systems management should be modified to more closely match water deliveries with farmer needs. In some situations, this would require increased investment in physical infrastructure, for example, measuring and control devices, but in others it

[5]Although the electricity monitoring capability exists, only rarely is it used.

would primarily require improved information flows, more careful monitoring, and a change to a "client orientation."

Fourth, to accommodate the probable reduction in available water at the farm level, there is a need for improvement in agricultural practices. Opportunities to save water through shorter-season varieties, changes in timing of planting, and/or improved on-farm water distribution are possible.

To the extent that the foregoing does not take place, we can expect reductions in area devoted to rice production, increased movement to higher-value crops in areas with continuing irrigation capability, and increased rainfed cropping.

Finally, although it takes time to develop irrigation infrastructure, it requires even more time to improve irrigation and water resource management. And, time is not on our side. Water is a key to food security. It seems fair to say that the challenge we face today is as great as or greater than that faced half a century ago on the eve of the Green Revolution.

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Notes

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Rice pest management: issues and opportunities

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Introduction

Rice fields are managed ecosystems in which a large diversity of floral, faunal, and microbial species provides a wide range of services for human well-being (MEA 2005). Most of these species do not reduce production; indeed, many are beneficial, such as predators, parasitoids, flowering plants, and soil bacteria. However, a few species become pests, that is to say, they are responsible for crop losses exceeding acceptable thresholds, mostly when they occur in high densities. They then can affect production and threaten food security. Although much of the literature on crop losses has focused on biomass (yield) loss, comparatively little research has dealt with qualitative losses (Savary et al 2006a). Qualitative losses include quarantine diseases, which prevent seed sales, and, more importantly, diseases that produce toxins that affect food safety. In many cases, pest species, especially insects, are regulated by the diversity of natural enemies associated with agroecosystems. The most important ecosystem service that rice cultivation provides to humans is food provisioning (MEA 2005). In many societies, especially in Asia, rice also provides a key cultural service as well. The regulatory systems that support ecosystem services, if properly managed, can continue to sustain these services for centuries.

The Green Revolution that began in the 1960s triggered a cascade of technological events in plant protection. In particular, pesticide use on rice, especially insecticides, increased with the adoption of rice varieties that lacked resistance to many pests (animal pests and pathogens). Recommended technology packages for rice in the 1960s and ’70s usually included insecticides, especially organochlorines. These insecticides not only killed insect pests, but their natural predators as well. Natural regulation of pests in rice ecosystems was disrupted, creating a favorable environment for pest species such as planthoppers. By the 1980s, insecticide resistance became an increasing problem, especially for organophosphates and carbamates that were replacing organochlorines. Farmers responded by increasing dosages or by combining several chemicals in toxic mixtures. As a result, even more natural predators were killed, insecticide resistance buildup was accelerated, and human health and the environment were further threatened. Other factors affecting the resilience of rice ecosystems have been associated with measures taken to increase rice production profitability, such as year-round cultivation of rice on the same land (creating favorable conditions for pest outbreaks) and higher nitrogen applications to the higher-yielding rice varieties (enhancing their susceptibility to some pathogens and insects).

It became clear that alternative approaches to rice pest management were needed. With respect to key rice diseases, rapid progress was made to develop varieties with suitable resistances (Jena and Mackill 2008, Zeigler and Savary 2009) and in many cases, particularly resistance to diseases, these varieties were successful (Bonman et al 1992, Jena and Mackill 2008). Governments began to rethink the need for policies to subsidize pesticide use. They also began to tighten pesticide regulations and enforce them more strictly in several rice-growing countries. Integrated pest management (IPM) approaches were developed that encouraged farmers to restrict their use of pesticides to situations when economic loss might be expected (Teng 1994).

However, several forces have combined to keep pesticide use relatively high on rice despite growing evidence that pesticide applications, at least for insects and diseases, can often be counterproductive due to the adverse effects on beneficial organisms and the natural balance:

1. Farmers, policymakers, and other officials have grown accustomed to applying pesticides as "medicine" to cure pest problems, in many cases as preventive medicine, and as "insurance" against injuries (Zadoks 1985), "problems" that may in fact cause little yield loss.
2. Driven by an understandable motive for profit, chemical companies run intensive marketing campaigns led by a cadre of salespeople who are a constant presence in rice-growing areas.
3. As farm wages have increased due to economic growth in Asia, herbicides have increasingly been substituted for hand weeding (Naylor 1996), a trend necessitated by the transition from transplanting to direct seeding of rice (Pandey and Velasco 2005). In Asia, approximately 20% of the rice area is direct seeded though local variation is considerable: almost all of southern Vietnam and the Malay peninsula are direct seeded, while transplanting predominates in Indonesia and Bangladesh. Weeds are the cause of the highest chronic yield losses in rice (Savary et al 2000b).
4. IPM approaches are often information-intensive, and few countries have applied innovative low-cost methods for reaching large numbers of farmers with IPM messages on a continual basis. Without such methods, the frequent repetitive messages from chemical companies predominate and cause discontinuance of learned practices (Escalada et al 2009).
5. The main rice varieties grown over large areas are still susceptible to pests or varietal resistance can be overcome despite continual progress in breeding multiple resistance in cultivated rice varieties (Bonman et al 1992, Jena and Mackill 2008). High insecticide use tends to speed up resistance breakdown in varieties (Gallagher et al 1994). In the 1990s, farmers in Vietnam used mainly organophosphates and carbamates, which remained dominant (35% of sprays) in the 2000s (Escalada et al 2009). It has been shown that, by reducing insecticide use, especially in the early crop stages, natural enemy biodiversity would return to rice fields in sufficient quantity to manage insect pests (Heong et al 2008). But some still question this conclusion, including policymakers who affect national pesticide policies.

The future of pest management in rice, however, holds promise for reduced pests and eventually reduced pesticide use. Plant breeding will become more efficient as molecular-assisted breeding speeds up the process for breeding in pest resistance, and as IPM becomes more widespread with improved practices, enhanced methods for disseminating information to farmers, and corresponding support policies. Ecological engineering techniques (Gurr et al 2004, Gurr 2009) may help to conserve or restore regulatory ecosystem services to reduce pest problems in rice. In some cases, genetically modified organisms (GMOs) may play a significant role in reducing pest problems and pesticide use. China, for example, has given biosafety approval for *Bt* rice for the control of the rice-borer pest, and approval for large-scale commercial release can be expected in 2–3 years (IRRI 2010). This is expected to result in a large-scale reduction in insecticide use, although some believe that pesticide use by Chinese farmers is influenced as much by perception as by pest pressure. Thus, a significant reduction in insecticide use may depend on a concurrent strong stewardship program aimed at insecticide reduction (Heong and Escalada 2007b, Cohen et al 2008).

This chapter provides an overview of the pest management situation in rice and the factors that will influence the use of alternative pest management practices in the future. We examine rice pests and losses; pesticide use on rice; economic, environmental, and health impacts of pest management practices on rice; policies and regulations that influence pesticide use and alternative pest management practices; and the potential for IPM and biotechnologies to play larger roles in future rice pest management.

Rice pests and losses

Rice pests

A large variety of insects (more than 100) feed on rice, although most are not economically damaging enough to require any management practices. The rice plant has strong compensatory abilities to recover from such injuries (Rubia et al 1996) if they occur in the vegetative stage. The relative importance of rice insect pests varies from country to country, although the planthoppers—brown planthopper (BPH), *Nilparvata lugens*; the whitebacked planthopper (WBPH), *Sogatella furcifera*; and small brown planthopper (SBPH), *Laodelphax striatellus*—affect most rice-growing areas. Major rice-producing countries such as China, Vietnam, India, and Thailand have recently experienced serious problems (see http://ricehoppers.net/). Several stem borers and leaf-feeding insects are also found in most rice-growing areas. Stem borer species such as the yellow stem borer (YSB), *Schoenobius incertulas,* and the striped stem borer (SSB), *Chilo supressalis,* can sometimes cause major yield losses. The YSB is dominant in most tropical and subtropical areas, while the SSB occurs mainly in temperate rice. Leaf feeders, such as the rice leaf folder (RLF), *Cnaphalocrocis medinalis,* often attack rice in the early crop stages, causing highly visible leaf injury, but, because of plant compensation, the injury often does not translate into a yield loss (Graf et al 1992).

A wide range of rice diseases affect rice (Ou 1987), among which blast, sheath blight, bacterial blight, brown spot, and several virus diseases, including rice tungro, are of primary concern. As with insect pests, rice diseases can be categorized as chronic yield reducers (e.g., brown spot and sheath blight), whereas other diseases cause sporadic, often large-scale, and extremely damaging epidemics (e.g., blast and most virus diseases; Zeigler and Savary 2009). Such uncertainty of risk adds another layer of complexity to assessing priorities and developing sustainable decision-making processes, from the field to the national scales.

A broad spectrum of weeds (Moody 1991) is present in all rice-growing areas. For example, 140 species are commonly associated with direct-seeded rice (Rao et al 2007) and the grasses, such as *Echinochloa* species, are a major constraint on rice worldwide. In aerobic rice cultivation, nematodes are considered an emerging problem.

Although few data are available, rodents are also a problem for cereal production (Stenseth et al 2003, Meerburg et al 2009), and are thought by many to cause 5–10% preharvest rice production losses in Asia (Singleton 2003). The highest chronic rice losses due to rodents are in Indonesia; in West Java, mean annual losses are estimated at about 17% (Singleton et al 2005). Family rice plots are small, and it is not uncommon for farmers or villagers to lose half of their entire rice crop to rats. Occasionally, especially in upland rice environments, rodent populations erupt, with dramatic effects on highly vulnerable and food-insecure families. Accurate estimation of losses due to rodents is complicated by the fact that damage is patchy in space and time. The sporadic nature of losses may account for the wide differences in estimates. For example, the RICEPEST model places them at less than 1% (Table 1).

Crop losses

Crop loss assessment is a research field in its own right, and information on crop losses, even for such a major crop as rice, is patchy for several reasons. First, crop losses are derived from both direct and indirect effects. Indirect effects include losses in quality as well as indirect economic losses (Chiarappa 1971). Second, quantitative yield losses due to pests such as insects, diseases, and weeds are not additive, especially in rice (Padwick 1956, Pinstrup-Andersen et al 1976). Third, observed injuries do not necessarily translate into quantitative yield losses (Savary et al 2006a), as plants can compensate, especially for foliar damage early in the season. Fourth, in most cases, a crop is exposed to not one but several injuries during the season, resulting in a crop health syndrome (Savary et al 2006b), that is to say, a combination of injuries due to diseases and insects encountered by a crop during its cycle in a given production context. Crop health syndromes depend on production situations, as demonstrated in a range of agroecosystems, including rice-based systems (Savary et al 2006a). Since production situations evolve rapidly, so do crop health syndromes, and thus the importance of specific pests.

Because of these factors, yield loss estimates differ considerably from one source to another. Oerke (2006) estimates global crop losses in rice due to weeds, animal pests, and diseases at 10.2%, 15.1%, and 12.2% of the attainable yield, respectively. It is worth noting that these estimates were derived from pesticide industry estimates, with the result that (1) some "pests"—diseases, weeds, animal pests—tend to be

Table 1. Estimated yield loss due to rice pests under current conditions, and estimated yield gain due to the application of pest management tools based on the RICEPEST simulation model.

Item	Current estimated yield loss		Estimated yield gain due to available pest management tools[a]	
	Absolute[a] (t/ha)	%	Absolute[b] (t/ha)	%
Injury profile[c]	1.4–2.3	25–43	1.2–5.7	16–69
Bacterial blight	0–0.03	0–0.6	0–0.9	0–17
Sheath blight	0.3–0.7	5–10	0–2.4	0–29
Brown spot	0–0.5	0–10	0	0
Leaf blast	0–0.1	0–1.7	0–3.5	0–65
Neck blast	0–0.1	0–2.1	0–2.1	0–40
Sheath rot	0.1–0.4	1.3–7.3	0	0
Brown planthopper	0–0.01	0–0.3	0.1–0.3	0.8–5.3
Defoliating insects	0.01–0.05	0.2–0.9	0–0.1	0.1–0.9
Deadhearts (stem borers)	0.02–0.05	0.3–1.0	0.02–0.12	0.3–2.3
Whiteheads (stem borers)	0.1–0.3	1.9–5.8	0.1–0.7	1.9–13.2
Weeds	0.7–1.2	12–22	0.5–3.1	9–51
Snails		Trace*		
Rats		Trace*		
Birds		Trace*		

[a]Simulated gains, relative to current attainable yields, from applying available management tools, including host-plant resistance, crop management, and pesticides. [b]Estimates are provided as ranges across prevailing production situations. [c]Injury profile refers to the combination of injuries caused by weeds, diseases, insects, and animal pests, occurring during a cropping season in a given production situation. *Trace: indicates less than 1% relative yield loss in the [production situation * injury profile] combination, where the mode of corresponding injury is the highest.
Source: Willocquet et al (2004).

overrepresented (pesticide trials do not report nonsignificant results on an individual yield-reducing agent), (2) interaction among yield-reducing agents is ignored, and (3) yield-reducing agents for which no pesticide exists (or for which pesticide use is deemed unprofitable by the chemical industry) are ignored (Savary et al 1998). An example of the latter is rice brown spot (*Bipolaris oryzae*), the "poor farmers' field disease," which causes severe and chronic losses in South and Southeast Asia (Savary et al 2000a, b).

The complexity involved in estimating crop losses suggests the need to develop a modeling approach. RICEPEST (Willocquet et al 2004) is specifically designed to address this need. It capitalizes on long-term, widespread surveys (Savary et al 2000a) and experiments (Savary et al 2000b) conducted by the International Rice Research Institute (IRRI) and its partners. Modeling also enables us to estimate gains from applying pest management tools. A summary of estimated yield losses and gains due to the use of pest management tools is provided in Table 1. These results pertain to tropical Asian lowland (irrigated and rainfed) ecosystems.

Pesticide use on rice

Data on rice pesticide sales for various countries are difficult to obtain given their proprietary nature, but some data are available for the period 1980-96 from IRRI (at http://beta.irri.org/solutions/index.php?option=com_content&task=view&id=250), and a few estimates are available for more recent years. Summarized sales data presented in Tables 2–5 indicate that sales of all pesticides (i.e., insecticides, fungicides, and herbicides) grew over time in most countries until the mid-1990s, but have generally stagnated or recently declined, especially in real terms (removing inflation). Fewer pesticides are being used now, but on a larger area (especially for herbicides), and the introduction of products with higher biological activity and lower application rates means that the amount of pesticides per hectare has declined. Data in Table 2 must be interpreted with caution as the 2007 data are available at the distributor level while data for earlier years are at the grower level. In an attempt to make them comparable, the distributor-level data were multiplied by a 25% markup. Markups vary by chemical, however, and therefore these data should be viewed as only approximate. Other evidence also indicates that there may have been a decline in rice pesticide sales in the late 1990s and an upward trend again from 2001 to 2007. In summary, pesticide use roughly doubled from 1980 to 1996 but has leveled off since then in real terms.

Pesticide application per hectare varies dramatically by country. Japan, with only a little over 1% of the rice area planted, used a third of all pesticides in 2007. However, that proportion is down from around half in earlier years, with pesticide use in China, Republic of Korea, and India growing substantially over time. In addition, pesticide prices may differ by country, and are likely to be lower in China than in Japan, for example. Therefore, the increase in pounds of active ingredient in China may be even larger than the sales data suggest.

Rice herbicide sales (Table 3) show that Japan is still the dominant leader, but China, Republic of Korea, the United States, and Brazil have moved up substantially. On a percentage basis, India has seen its herbicide sales grow rapidly, but it was starting from a small base and it applies less per hectare than most other countries. India has more rice hectares than any other country, with 44 million ha in 2007. The United States has seen its rice herbicide sales drop substantially since the mid-1990s. Overall, herbicide sales have increased as a proportion of total pesticide sales, primarily due to growth in countries such as China that have experienced rising and higher labor costs for hand weeding. One reason the overall market has been stagnant is that the rice area cultivated in Japan and Republic of Korea has declined following an opening up of their markets following international trade negotiations.

Japan has the largest share of the rice insecticide market (Table 4), but its dominance is less than it is for herbicides and fungicides and its share has been declining since the late 1980s. The shares of China and India have grown, with the possibility that China may overtake Japan as the leading insecticide-using country in the future. Republic of Korea and India are the only countries besides China and India with more than US$100 million in sales. In real terms, rice insecticide sales have declined gradually since the late 1980s. Insecticide sales are volatile in individual countries from year to year due to the sporadic nature of certain insect outbreaks.

Japan dominates the rice fungicide market (Table 5) but its share has declined steadily from more than 60% in 1980 to 40% in 2007, due in part to the decline in rice area. Fungicide sales in China, Republic of Korea, and India have grown, although the market is smaller across the board than it is for herbicides and insecticides.

Costs associated with pesticide use on rice

Pesticides are often applied on rice in Asia from two to eight times per season (Huang et al 2003) and make up 2% to 7% of the value of gross production (Table 6). Huang et al (2003) found that pesticides accounted for 7–8% of input costs on rice in China. The relatively low cost of pesticides in relation to farmers' perceptions of potential production losses is a major factor explaining current pesticide usage. The available yield loss data illustrate this point. Current pest management practices, which are heavily dependent on pesticides for managing insect pests and many diseases, still result in yield losses of approximately 10–15%, but losses would be much higher without pest management. Similarly for weeds, losses are about 15–20% under current weed control and would be much higher otherwise. The wide gap between current and potential yield losses for weeds is of concern because current weed control practices in many areas often involve hand weeding. As noted above, as labor costs continue to rise, we can expect an increase in herbicide use.

Four major hidden costs are not reflected in the direct economic costs of pesticide use. The first is the cost associated with the long-term buildup of resistance to pesticides, the second is the effect that pesticides can have on natural predators of pests, the third is the acute and chronic effects of pesticide exposure on human health, and the fourth is the long-term effects of pesticides on other ecosystem services.

Table 2. Global rice pesticide (insecticide, fungicide, herbicide) sales (million 2000 US$), selected years.[a]

Region	1980	1988	1996	2007
Japan	700	1,849	1,636	1,043
China	120	251	430	400
Republic of Korea	61	205	405	290
India	89	219	225	244
Vietnam	19	34	44	123
United States	117	115	229	113
Brazil	81	95	93	113
Rest of world	387	587	542	800
Total	1,574	3,355	3,607	3,125

[a]Sales data at the grower level in nominal prices for the years 1980, 1988, and 1996 were obtained from IRRI (http://beta.irri.org/solutions/index.php?option=com_content&task=view&id=250). For 2007, the data in nominal prices were obtained from Phillips McDougall AgriService at the distributor level and adjusted by a 25% mark-up to approximate grower-level values. Nominal data were subsequently deflated using International Monetary Fund GDP price deflator for the United States to convert the series in terms of constant prices at year 2000.

Table 3. Global rice herbicide sales (million 2000 US$), selected years.[a]

Region	1980	1988	1996	2007
Japan	459	753	703	490
China	19	11	51	125
Republic of Korea	15	37	117	84
India	15	26	28	50
United States	78	81	194	86
Brazil	37	42	75	73
Rest of world	119	219	196	436
Total	741	1,169	1,363	1,343

[a]Sales data at the grower level in nominal prices for the years 1980, 1988, and 1996 were obtained from IRRI (http://beta.irri.org/solutions/index.php?option=com_content&task=view&id=250). For 2007, the data in nominal prices were obtained from Phillips McDougall AgriService at the distributor level and adjusted by a 25% mark-up to approximate grower-level values. Nominal data were subsequently deflated using International Monetary Fund GDP price deflator for the United States to convert the series in terms of constant prices at year 2000.

Table 4. Global rice insecticide sales (million 2000 US$), selected years.[a]

Region	1980	1988	1996	2007
Japan	241	594	419	253
China	102	196	213	204
Republic of Korea	46	86	154	105
India	74	169	154	146
Indonesia	33	99	46	23
Rest of world	337	236	228	314
Total	833	1,380	1,214	1,073

[a]Sales data at the grower level in nominal prices for the years 1980, 1988, and 1996 were obtained from IRRI (http://beta.irri.org/solutions/index.php?option=com_content&task=view&id=250). For 2007, the data in nominal prices were obtained from Phillips McDougall AgriService at the distributor level and adjusted by a 25% mark-up to approximate grower-level values. Nominal data were subsequently deflated using International Monetary Fund GDP price deflator for the United States to convert the series in terms of constant prices at year 2000.

Table 5. Global rice fungicide sales (million 2000 US$), selected years.[a]

Region	1980	1988	1996	2007
Japan	381	502	514	259
China	64	45	67	66
Republic of Korea	44	82	133	99
India	24	24	43	48
United States	0	5	28	19
Rest of World	96	79	142	150
Total	609	737	927	643

[a]Sales data at the grower level in nominal prices for the years 1980, 1988, and 1996 were obtained from IRRI (http://beta.irri.org/solutions/index.php?option=com_content&task=view&id=250). For 2007, the data in nominal prices were obtained from Phillips McDougall AgriService at the distributor level and adjusted by a 25% mark-up to approximate grower-level values. Nominal data were subsequently deflated using International Monetary Fund GDP price deflator for the United States to convert the series in terms of constant prices at year 2000.

Table 6. Pesticide use on rice at selected sites in Asia (1994-99).

Site	Insecticides (kg a.i./ha/season)	Herbicides (kg a.i./ha/season)	Others (kg a.i./ha/season)	Total (kg a.i./ha/season)	Pesticide costs as a percentage of gross value of production
Tamil Nadu, India	0.29	0.11	0.01	0.41	0.5
Central Luzon, Philippines	0.18	0.34	0.18	0.70	2.3
Mekong, Delta, Vietnam	0.51	0.49	0.10	1.10	3.8
Red River Delta, Vietnam	0.61	0.65	0.34	1.60	2.5
West Java, Indonesia	0.62	0.69	0.54	1.85	4.4
Central Plain, Thailand	0.97	0.89	0.25	2.10	7.0
Zhejiang, China	3.96	0.09	0.17	4.23	3.0

Source: Dawe D. The Second Green Revolution – trends and implications in pesticide use, IRRI Rice Knowledge Bank, www.knowledgebank.irri.org/ipm/index.php/pesticide-use-revolution-crop-health-2739/251-the-costs-of-pesticide-use.

Pesticide resistance and ecosystem disruption

The buildup of pesticide resistance over time can lead farmers to apply larger amounts of more toxic chemicals to manage pest outbreaks. Planthopper populations in China and Vietnam, for instance, have developed more than 200-fold resistance to some insecticides such as the neonicotinoids (Matsumura et al 2009). The negative effects on natural predators cause an ecological imbalance that leads to pest outbreaks. Insecticides that have adverse effects on nontarget beneficial arthropods such as bees, spiders, parasitoids, and aquatic fauna lead to a phenomenon in the ecosystem called "catastrophic synchronization" (Waage 1989). This phenomenon causes not only high predator mortality but also a disorganization of the food web structure, thus rendering predators ineffective (Heong and Schoenly 1998). For example, in the 1980s, excessive pesticide use decimated insects that preyed on brown planthoppers and disorganized the food web structures in Indonesia, resulting in a serious outbreak of planthoppers (Dawe 2002). Similar outbreaks routinely affect about a million ha in China every year (Cheng 2009).

Planthopper outbreaks are affected by the amount, timing, and types of pesticides that decimate BPH natural enemies (Heong 1996). BPH outbreaks have occurred recently in Thailand, China, and India (Heong 2009). Secondary pest problems occur after pesticides have been applied to control a different pest early in the season. Broad-spectrum pesticides are often applied that are highly toxic to bees, parasitoids and predators, and aquatic fauna. Examples of these chemicals are chlorpyrifos, cypermethrin, and avemectin. Their effects on causing planthopper outbreaks have been widely documented and discussed (Heong and Schoenly 1998 and Way and Heong 1994 provide reviews).

Buildup of resistance to chemicals is also a problem with weeds. Across all crops, 341 herbicide-resistant biotypes in 194 species have been reported (weedscience.org 2009). Although herbicide resistance in rice weeds in Asia lags behind other areas, possibly due to continued use of hand weeding and cultural practices such as flooding, several instances of resistance have been reported. Repeated herbicide application can also disrupt rice ecosystems and alter weed species composition, rendering the herbicides less effective. For example, in wet-seeded rice in Malaysia, application of 2,4-D resulted in the dominance of the grass *Echinochloa crus-galli*, whereas applying graminicides (e.g., quinclorac, pretilachlor, or propanil) promoted *Monochoria vaginalis* (Man and Mortimer 2002). Likewise, repeated applications of benthiocarb and propanil, over four seasons, led to the elimination of *E. crus-galli* but increased the proportion of *Scirpus* spp. sedges.

Impacts on human health and the environment

Acute and chronic health problems associated with pesticide use on rice have been well documented (Rola and Pingali 1993, Pingali et al 1994, Pingali and Roger 1995, Antle and Pingali 1994, Dasgupta et al 2006, Devi 2007). IRRI assessed the health and environmental costs of using pesticides in rice production in the Philippines and found them to exceed the economic benefits (Rola and Pingali 1993, Pingali and

Roger 1995). Applicators suffer acute and chronic health problems that reduce rice productivity. The major concern about pesticide use on rice is misuse as much as overuse, in other words, applying the wrong pesticide at the wrong time in the wrong amount with inadequate applicator protection. Clinical studies conducted on rice and vegetable farmers in Indonesia, the Philippines, and Vietnam found that most of the farmers exposed to pesticides experienced at least one negative health effect (Rola and Pingali 1993, Antle and Pingali 1994, Kishi et al 1995, Xuyen et al 1998). In Bangladesh, 37% of the farmers using conventional pest management reported health problems such as eye irritation, headaches, dizziness, vomiting, shortness of breath, skin effects, and convulsions (Dasgupta et al 2006).

Rice paddies include a vast array of vertebrate and invertebrate organisms (Pingali and Roger 1995). Major vertebrates include fish, frogs, and rats, while invertebrates include crustaceans, micro-crustaceans, aquatic insects and insect larvae, snails, worms, algae, and bacteria. The rural poor depend on consuming fish, shrimp, and other organisms from rice paddies, while nutrient recycling occurs in paddy soils through interactions among micro- and macro-organisms (Pingali and Roger 1995). Therefore, these organisms must be in balance to maintain human nutrition and soil fertility.

Pesticide use has numerous effects in the food chain associated with rice production, including effects on species number, relative composition of species, and residue accumulation in surviving populations. Pingali and Roger (1995) draw on the literature and detail those effects. The following is a brief summary of pesticide effects, based on their results: (1) the number of aquatic vertebrates declines rapidly with pesticide use; (2) pesticide residues in surviving populations of vertebrates tend to be low; (3) invertebrate populations suffer relatively small effects due to a reduction in predator populations such as fish and frogs; (4) worm populations decline, which reduces fish food and soil aeration; (5) algae blooms occur at first but later decline; (6) long-term detrimental effects on microbial populations are few; and (7) the pest-predator balance is disrupted, leading to pest resurgence and development of secondary pest problems. Insecticide effects on the rice arthropod community have been studied by Cohen et al (1994), Schoenly et al (1995), and Heong and Schoenly (1998). The effects of insecticides were shown to translate into ecological costs in the form of (1) food-chain-length reduction from about 3 to 2, making the sprayed fields more vulnerable to pest re-colonization; (2) disorganization of pest–natural enemy–other species relationships, and the food web structure as a whole; and (3) r-strategist[1] arthropods, such as planthoppers, were favored. When insecticide pressures decreased, arthropod biodiversity doubled and pest abundances declined (Heong et al 2007).

In addition to in-crop effects, a number of off-crop effects occur as vertebrates accumulate pesticide residues from drainage ditches and irrigation canals in fully irrigated (flooded) systems. Poorer farmers in many areas harvest snails, fish, crabs, and

[1]The r-strategists are opportunists, selected for the characteristic of maximizing food intake, having high reproductive capacities, having high migratory abilities, and exploiting their ephemeral habitats. These species become pests when released from their natural biological controls (Southwood and Comins 1976).

aquatic plants from these ditches and canals (Tejada and Magallona 1985). Groundwater contamination also occurs, resulting in well-water contamination (Bhuiyan and Castañeda 1995).

Driving forces and alternatives for rice pest management

Major forces driving rice pesticide use, and rice pest management in general, include the development of alternative technologies, including the breeding of host-plant resistance among others; genetically modified (GM) rice varieties; rising labor costs, which affect herbicide use, rice policies, and prices; improved educational means of reaching growers with IPM messages at lower cost; pesticide prices; changes in pesticide regulations; and climate change. Labor costs continue to rise as incomes grow, and will continue to result in increased use of herbicides on rice in developing countries, especially in Asia, unless alternative weed management practices are developed and delivered. Herbicide use in Japan may decline due to a government policy to gradually reduce rice area. However, continued growth in demand for rice worldwide, especially in Asia, may exert upward pressure not only on rice prices but also on pesticide demand.

Biotechnology

Biotechnology is just beginning to play a role in the development of alternatives to pesticide use and is likely to play a key role in the future. *Bt* rice has obtained biosafety certificates and is awaiting approval by the Ministry of Agriculture in China for stem borer control (Oryza 2010), and is also under development in other countries. Punjab Agricultural University in India is developing a *Bt* rice with resistance to leaffolders. Other GMOs have been developed and are awaiting regulatory or market approval.

Herbicide-tolerant Roundup Ready rice and Liberty Link rice have been available for some time, but have not been a high priority for release by the companies involved because of concerns over consumer acceptance. These varieties, if released in the U.S. and Japan, would result in a substitution among herbicides. However, in most developing countries, the varieties would likely increase herbicide use as a substitute for labor. Clearfield rice, a herbicide-resistant non-GM variety, has been released in the Americas, and applications for its approval have been made in Asia as well. Malaysia recently released Clearfield rice particularly to manage weedy-rice problems.

Although GMOs have potential to reduce pesticide use overall, most of them will not be released for several years because of regulatory delays and market concerns. For instance, *Bt* cotton has become widespread in the United States, China, and India, but approval for GM rice has been much slower. Being a food crop, rice has drawn more attention from groups opposed to transgenic crops. As a result, public agencies have been cautious both in research and in the regulatory process. Private companies have been cautious because of market concerns and because rice is mostly a self-pollinated crop, which makes it harder to manage the intellectual property. It is possible that the

Bt rice in China, if approved for wide-scale production, will break the logjam on GM rice, if it proves to be profitable and reduces insecticides as promised. Evidence with data from experimental trials indicates that it will be so as a result of a large reduction in pesticide use in China even though the yield advantage may be small (Huang et al 2008, Wang et al 2010, Hui et al 2010). As noted above, some question how much *Bt* rice will reduce insecticide use in China unless there is a strong market campaign to change farmers' perceptions (Heong et al 2005, Cohen et al 2008).

Other pest-resistant rice varieties are under development through marker-assisted breeding (Jena and Mackill 2008). These varieties will not require stringent regulatory approval because they are not GMOs. The rice genome has been mapped for about 10 years now, and molecular-assisted breeding is being used at IRRI and in several national research systems to speed up the breeding for multiple pest resistance. The potential of resulting improved varieties to reduce pesticide use is significant if they are introduced with effective educational programs. We say improved and not new because the idea is to breed the resistance into mega-varieties that are already popular with farmers to help encourage widespread adoption. Varieties with resistance to bacterial leaf blight (BLB) that were developed using molecular markers are already available to farmers in Indonesia and China (Huang et al 2008).

In addition to host-plant resistance to diseases and animal pests, other methods can help reduce crop losses. The use of bio-pesticides, rotating rice with other crops, and altered planting dates are just a few. Simply improving crop health through proper fertility and water management can help as rice is a crop with a significant ability to compensate for injuries during the growing season if it is in an otherwise favorable production situation. Minimizing chemical use also helps to conserve beneficial insects, which can help keep insect pests in check. The growth of beneficial insect populations may also be stimulated by introducing nectar-rich flowers on the bunds and borders of rice areas (Gurr et al 2004, Gurr 2009). Promotion of IPM may overcome the effects of sales campaigns for pesticides, but, unfortunately, unless educational efforts are on a larger scale than at present across Asia and sustained, progress will be slow. Innovative efforts such as those by IRRI in Vietnam that use radio soap opera (Heong at al 2008) and multimedia campaigns (Escalada et al 1998, Heong et al 2008) to reach large numbers of growers will be required, in combination with continued improvement and enforcement of pesticide policies and regulations. If nonchemical alternatives can be found and disseminated in a sustainable manner, the long-run result will be a more sustainable rice culture.

Resistance problems can occur not only with pesticides but also with biotechnology solutions. To slow the development of pest resistance to biotech products on other crops, farmers have been asked to follow stewardship guidelines. For example, to preserve the efficacy of the "Clearfield" herbicide-resistance technology, rigorous guidelines are in place involving crop rotations, number of herbicide applications, and fallow management (BASF 2010). Likewise, farmers growing *Bt* corn in the United States are required to maintain a refuge around their corn fields to reduce the chances that insects that survive the *Bt* corn will breed with each other and produce resistant offspring. Many farmers do not follow these guidelines, however, and enforcing them is even more of a challenge in a developing country. For *Bt* rice, resistance management will require farmers to maintain a refuge as well. Because rice stem borers are monophagous, widespread planting of *Bt* rice may quickly lead to the development of resistance (Cohen et al 2008).

Pesticide policies and regulations

A vast array of pesticide policies and regulations influence the use of pesticide and alternative pest management practices on rice. Although most developed countries such as the United States have more refined environmental regulations and food safety policies than do developing nations, most rice-producing countries have gradually tightened their pesticide rules in recent years. Twenty years ago, it was not uncommon to find no regulation of pesticides, regardless of toxicity. Today, most countries (at least nominally) abide by international standards for food safety developed by the CODEX Alimentarius Commission of FAO/WHO. That commission is an international body that sets guidelines on pesticide residue amounts that are considered in safety evaluations for approval of specific pesticides.

Most countries now use the WHO recommended classification of pesticide hazard in deciding how to classify and restrict specific chemicals. Individual products are classified in a series of tables, according to oral or dermal toxicity of the technical product, and its physical state (solid or liquid). Each product falls under one of four groups: (Ia) extremely hazardous, (Ib) highly hazardous, (II) moderately hazardous, and (III) slightly hazardous. Some major rice-producing countries have banned most Class Ia and Ib pesticides on rice even if they allow them for restricted use for other purposes. Pesticides such as monocrotophos, methyl-parathion, azinphosmethyl, and carbofuran are all Class I chemicals that were commonly used on rice (Heong and Escalada 1997b, Litsinger et al 2009) but have seen increased restrictions fairly recently. However, many of these chemicals still exist even in countries where they have been banned or otherwise restricted, and they find their way onto rice paddies. Even after regulations are in place, it can take years for enforcement to catch up with the millions of pesticide dealers and farmers who may be slow to abide by the regulations (see Box 1).

Almost every country producing rice has in place regulations that follow international guidelines and involve registration of pesticides only after field testing at multiple sites over at least 2 years. Data are provided on chemistry, toxicity, efficacy, and residues. However, key factors that continue to cause health and environmental issues are the continual use of nonregistered chemicals and the misuse (Tjornhom et al 1997) of all chemicals. For instance, Heong et al (1995a) found that, in the Philippines, more than 80% of farmers' insecticide sprays were deemed as misuse. Insufficient pesticide education is part of the problem, but incorrect information provided by local pesticide dealers is also a serious issue. In addition, many Asian countries do not regulate the use of multiple trade names for the same active ingredient. For example, in China, the same active ingredient is sold in some cases under more than 500 trade

Box 1. Pesticide policies in the Philippines

In the Philippines, a joint study led by IRRI and the University of the Philippines in Los Baños found that, in the late 1980s, farmers' health costs were greater than any economic benefits of the pesticides that at that time were being applied to rice (Jamora and Templeton 2008). In response, and in keeping with international protocols, the Fertilizer and Pesticide Authority (FPA) of the Philippines in the early to mid-1990s passed a new set of pesticide regulations that restricted the highly toxic chemicals commonly used on rice and encouraged safer pesticide practices. The use of all WHO Hazard Class I and some Hazard Class II pesticides was banned in 1994. However, enforcement and adoption of these regulations and practices took time. The importation and use of banned pesticides declined only gradually. A 2002 survey found that they were still heavily used (Palis et al 2006). However, a farmer survey in 2007 found that 93% of farmers said they no longer could find the banned chemicals in the marketplace and 90% said they no longer used them (Jamora and Templeton 2008). More than 99% of the pesticides actually applied were registered for use on rice in the Philippines. Of the registered chemicals used, 61% were Class II, 28% were Class III, and 11% were Class IV. The same survey found that safer pesticide practices were being followed than were found in a similar survey in 1991. Apparently, there has been some progress, albeit slow.

names. Because farmers purchase pesticides by trade names, they are often confused by them.

A number of other direct and indirect policies influence pesticides and pest management. First, countries have at various times directly subsidized pesticides to encourage their use. Those policies were found in the Philippines, Indonesia, Bangladesh, China, and many other countries, especially in the 1970s and '80s. For example, the Masagana 99 scheme in the Philippines subsidized pesticide use on rice from 1973 to 1986. Pesticide subsidies include not only subsidized pesticide prices but also the use of public extension services in promoting chemical use, as in China. In some cases, government-backed credit programs required the use of pesticides with the basic idea that they would reduce crop risk. Also, it is common for governments to maintain emergency budgets to purchase pesticides for free distribution when outbreaks occur or are reported (Farah 1993). Because of the time lag between the outbreak and release of funds, pesticides are often available to farmers only after the outbreak is over.

By the late 1980s, several countries began to rethink their pesticide subsidy policies. Health and environmental problems were becoming clearer, including the effects of chemicals on beneficial organisms. IPM programs were expanding in developed countries and beginning to draw attention in Asia as well. Pest resurgence was an increasing problem in rice as resistance built up to various chemicals. Economic difficulties in several countries also may have influenced them to reduce pesticide subsidies along with other public subsidies to agriculture. The removal of pesticide subsidies in Indonesia, for example, in the late 1980s is credited with reducing pesticide use in that country at the same time IPM programs were growing.

In some cases, pesticides were actually taxed through import tariffs on the technical (active ingredients) as well as the formulated product itself. The Philippines, for example, had a 10% tariff on the technical (active ingredient) product and a 3% tariff on formulated pesticides in the 1990s (Tjornhom et al 1998). These policies were altered in some countries as trade restrictions were modified following implementation of the Uruguay Round Trade Agreement. In some countries in Asia, exchange rates became overvalued in the 1990s and created an indirect subsidy to imports such as pesticides, and these indirect subsidies more than offset the tariffs (Tjornhom et al 1998). The Asian financial crisis squeezed out the overevaluation in most Asian countries, temporarily at least reducing those subsidies.

One factor that continues to strongly hinder adoption of bio-insecticides, bio-control agents, and pheromones as substitutes for synthetic chemicals in IPM programs, including rice IPM, is that they are often all treated in the same way as synthetic chemicals in the regulatory process. Pesticides are defined as any substance that is intended to prevent, destroy, attract, repel, or control a pest. Bio-pesticides or pheromones are considered pesticides even though they may be benign when it comes to effects on human health. As pesticides, they still must be examined and registered before their use is approved. Although everyone agrees with the need for registration, unless the registration process is streamlined for these substances that have consistently been found safe during testing elsewhere, their use may never spread. Many of these substances are locally produced biological products with local markets. Subjecting them to the complete review process is expensive. Chemical companies may fear their spread as they would reduce profits on sales of synthetic pesticides, and hence they have an interest in ensuring that bio-pesticides are slow to reach the market. The United States has streamlined the registration process for these types of products and other rice-producing countries should consider doing the same.

Improving and integrating rice pest management practices

Better management of pesticides through IPM strategies began with combining pest-resistant varieties with insecticide application decisions based on decision thresholds (Litsinger et al 2009). Economic injury levels for rice pests were studied by IRRI and by many national institutions in the 1970s and ’80s (Dyck et al 1981, Litsinger et al 1987, Teng, 1994) and formed the basis for establishing decision thresholds for pesticide use. Spraying pesticides, in principle, involves complex reasoning (Zadoks 1985). Not only do thresholds themselves vary with stage of crop growth, level of injury, crop price, and other factors, but certain expensive chemicals are more economical than inexpensive ones when applied in the recommended amounts. Therefore, threshold analysis is of limited use on rice except to indicate when spraying is clearly useless.

As discussed earlier, excessive and inappropriate use of pesticides can lead to the destruction of natural biological control services and to pest resurgence, secondary pest outbreaks, and the development of pesticide resistance (Heong 2009), but farmers have found it difficult to assess what, when, and how much to apply. Pesticide salesmen have influenced farmer decisions and the pesticide industry has lobbied governments to subsidize chemical use and relax pesticide regulations. Many farmers have been indoctrinated to the point that they are hesitant not to use pesticides (Matteson et al 1994). Problems with excessive pesticide use have gradually made some farmers more receptive to alternative IPM approaches, but IPM has often been pushed by scientists more than it has been demanded by farmers (Morse and Buhler 1997). In many cases, IPM scientists have not understood well enough the problems that farmers face and the wide influence of the chemical salesmen.

In an effort to overcome this disconnect between scientists and farmers, "farmer-first" approaches that were developed outside of IPM (Chambers et al 1989) were applied by IPM practitioners as well, first in farming systems research and extension and later in "farmer field schools" or FFS (Bartlett 2005). However, when the starting point was IPM, regardless of the approach, it still took scientists to lead, as farmers might have focused on other problems first if they had been given the choice. In many rice systems, farmers were more worried about constraints such as drought and floods than about pests.

The combination of excessive pesticide use, limited adoption of IPM by developing-country farmers, and the growth of farmer-first approaches led to the emergence of the FFS, first in Indonesia in the late 1980s, then elsewhere in Asia in the early 1990s, and later globally once it was institutionalized at FAO.[2] With FFS, instead of listening to talks or watching demonstrations, farmers observe, record, and discuss what is happening in their own fields from the time of planting until harvest. A typical FFS rice IPM program has 10–16 meetings, with about 25 farmers. The discovery and learning process is intended to provide an understanding of ecological concepts and their practical application. Since 1990, more than 2 million farmers have participated in farmer field schools in Asia alone (Bartlett 2005).

To some extent, the FFS approach to IPM diffusion has been controversial: it is strongly supported by some and disparaged by others. On the plus side, it has the advantage of involving high farmer participation, which makes it attractive not only to public institutions but also to grass-roots NGOs working in agriculture. It also has the advantage of having a well-defined set of steps that involve small group activities, making it possible to run a few or many FFSs depending on the budget. The hands-on involvement and intensity of the program help to reinforce its messages. It is one of the few approaches that help farmers understand the ecology of the system. On the negative side, the length and intensity of the program mean that it is costly per farmer reached compared with many other approaches—$25–50 per farmer participant is not uncommon (Ricker-Gilbert et al 2008). Therefore, given typical budgets for IPM diffusion, only a relatively small number of farmers can be reached. The hope has

[2]Under the leadership of Peter Kenmore, who had initiated the Indonesia program.

been that farmers who have been through an FFS program will train their neighbors. But, empirical studies have found little of this transfer of IPM knowledge (Feder et al 2004).

The assumption that farmers know a lot and that knowledge just has to be brought out of them is true but perhaps has been carried too far. The result is that farmers learn more about insects than they do about diseases because they can recognize insects more easily. Farmers know that they know a lot, but they also know that they do not know everything (Bentley 1989). Most farmers are receptive to at least trying new ideas when confronted with them, and will adopt them if they perceive the ideas make sense.

Partly because of the high cost of FFS and the slow spread of IPM messages, others working in rice IPM began experimenting with alternative approaches to disseminate IPM. Rather than trying to give complex messages to farmers, a few simple rules were developed by IRRI such as "Do not spray insecticides against leaf-feeding insects for the first 40 days of crop growth" (Heong et al 1998). IRRI had undertaken pest ecology studies and shown that the primary insect pests during the first 40 days are leaf-feeding insects, and that even high infestations could be tolerated by rice without significant yield loss (Heong 1990). Spraying insecticides for leaf-feeding insects in the first 40 days tends to remove beneficial predator insects, making the rice more susceptible to secondary pests such as brown planthoppers. Insecticides would then have to be sprayed again for the secondary pests.

Experiments were set up to test the efficacy of simple messages and they appeared to work well in the Philippines and Vietnam (Heong and Escalada 1997a, Heong et al 1995b). Farmers who received the messages reduced insecticide use by 50% after conducting an experiment to evaluate whether a simple rule of no spraying for 40 days after sowing (or 30 days after transplanting) would make a difference in their yields (Heong and Escalada 1997b). Simple messages are not a substitute for more in-depth farmer training, but can help in assuring that low-cost messages are received by large numbers of farmers to raise awareness and reduce pest problems and pesticide use.

More recently, the simple message concept was extended to the optimization of three critical inputs: seeds, fertilizer, and pesticides. IRRI and its partners implemented a program to stress three reductions of those inputs to (1) reduce the seeding rate with high-quality seeds and improved crop establishment, (2) optimize and thus prevent excessive N application through the use of a leaf color chart, and (3) reduce pesticide use through integrated pest management (Huan et al 2008). In Vietnam, the "Three Reductions, Three Gains" program used a radio drama, a television drama, a TV commercial, posters, flyers, and other extension efforts to promote the input reductions. This resulted in measured pesticide reductions of 13–33%, with higher yields and net incomes, and an improved environment (Huan et al 2008). But the results are variable, with Jamora and Templeton (2008) reporting only a modest gain.

Although IR8, the first high-yielding variety released with the Green Revolution in the late 1960s, was susceptible to many diseases and pests, varieties subsequently released had incorporated multiple resistance (Panda and Khush 1995). However, resistance is seldom complete and farmers were encouraged to continue to use pesticides for many years by pesticide dealers and others. Plant breeding efforts to build in further resistance have continued and modern varieties contain multiple genes for resistance in major rice-growing countries. IRRI has been instrumental in developing varieties with resistance to brown planthoppers, stem borers, green leafhoppers, tungro virus, blast, and bacterial blight. In fact, all IRRI-bred varieties are screened before release to ensure that they have at least a base level of resistance to these insects and diseases. More durable resistance is needed, and some progress has been made.

Breeding for pest resistance had become more efficient over time with the advent of new biotechnology tools. Despite the development of *Bt* rice with resistance to yellow stem borer in India, the Philippines, and China, no GM rice has been released commercially (although it appears that commercial release is close in China). However, marker-assisted selection (MAS) has been helpful for speeding up the breeding process for pest and nonpest traits. For example, IRRI developed lines with three bacterial blight resistance genes (*Xa4*, *Xa7*, and *Xa21*). As noted above, varieties developed through MAS for resistance to bacterial blight are currently available in Indonesia and China (Huang et al 2008).

MAS is particularly useful for developing tungo-resistant varieties due to the difficulty in screening for tungro resistance with conventional breeding (IRRI 2010). According to IRRI, progress has been made in defining the gene responsible for rice tungro spherical virus (RTSV) resistance. A gene (*Pi40*) with broad-spectrum resistance to multiple races of blast has also been identified through fine mapping. It is being incorporated in both indica and japonica breeding lines. A marker linked with brown planthopper resistance conferred by *Bph18* was MAS-validated in advanced backcross Japonica lines (IRRI 2009).

Weed control is another major concern and it has primarily been carried out through a combination of water management, hand weeding, and herbicides (Moody et al 1997, Labrada 2002). Few evidence-based agronomic recommendations and options are available to farmers to address emerging problems or reduce current weed losses. As a result, recent efforts have been undertaken to improve weed management and establish clear recommendations for farmers. “Palay Check” (or Rice Check”) is an example from the Philippines of an initiative to provide farmers with a complete set of recommendations, including integrating weed management into the recommended practices (PhilRice 2010). More commonly though, the most significant extension messages received by farmers are from herbicide suppliers and, with few exceptions, they emphasize herbicide use. In recent years, the development and release of herbicide-tolerant (HT) rice in the United States and Latin America has been a major innovation to overcome problems of weedy rice infestations. HT rice, however, has been accompanied by concerns over geneflow (e.g., Burgos et al 2008, Arroz 2009). Herbicide-tolerant rice is not yet available in Asia or Africa. In Asia, the availability of selective herbicides has become more widespread in addition to a wider range of products and formulations. Incidence of herbicide resistance in weeds is expected to “mirror” the situation that has occurred in other rice-growing areas, particularly in the Americas.

Future opportunities

Weed management methods

Herbicides have long been the main weed management method for rice in Latin America and North America, and in countries such as Japan and the Republic of Korea, and they are an important intervention in other Asian countries as well such as Sri Lanka and Vietnam (Rao et al 2007). Although herbicides are valuable in many rice systems and essential in others, diversified approaches could take advantage of ecological processes such as crop suppression of weeds, promoting seed predation and decay, and suppressing emergence to elevate the effectiveness of weed management in the long term. In this way, herbicides could be seen as a component of an integrated approach, which could reduce herbicide applications, lessen the risk of resistance, and slow the change in weed composition. Integrated weed management approaches have been advocated by several authors (e.g., Liebman and Gallandt 1997).

Rice farmers in Asia usually implement integrated weed control measures such as soil cultivation, flooding, and hand weeding to reduce weed infestation. Flooding is the most important weed management practice in many rice systems, since it suppresses the emergence and growth of most weed species. Flooding after herbicide application or hand weeding can largely prevent subsequent weed growth and reduce the need for further interventions. Successful herbicide application in lowland direct-seeded rice is closely linked to water management to achieve selective control while minimizing phytotoxicity (Hill et al 2001). In the future, however, many farmers will have limited irrigation water, which will restrict their capacity to use flooding as a weed control measure (Tuong et al 2005). Nonetheless, with only shallow and intermittent flooding, the growth of many weeds can be greatly reduced (e.g., Chauhan and Johnson 2009b). Where farmers have limited irrigation water, early rather than later flooding would also make the best use of water to control weeds as once the canopy of the rice crop has closed, shading from the crop is likely to suppress weed growth. Despite the widespread use of water to control weeds, there are many gaps in our knowledge regarding the use of timing and depth of flooding as possible means to exploit differential tolerances between the crop and weeds.

Choice of tillage systems or crop establishment practices can change the "trajectories" of weed population shifts. For example, in the rice-wheat cropping system in India, a buildup of *Ischaemum rugosum* in wet-seeded rice may be discouraged by using no-till systems in either rice or wheat (Singh et al 2008). Likewise, repeated use of no-till in rice may lead to greater densities of *Echinochloa colona* (Chauhan and Johnson 2009a), which could then be discouraged by shifting back to wet-seeded rice (Singh et al 2008). Cropping practices causing less soil disturbance, such as no-till, concentrate weed seeds near the soil surface (Chauhan and Johnson 2010). In these situations, high germination rates for many weed species are expected if moisture conditions are adequate. Seeds at or near the soil surface are also more prone to predation and desiccation due to unfavorable weather conditions (Jacob Spafford et al 2006, Mohler and Galford 1997). Seed decay and predation reduce the seed bank and number of weeds germinating in the following season. No-till or delayed tillage, which prolong seed exposure to predators, could be incorporated into integrated weed management programs. Retaining crop residues as mulch on the soil surface has the potential to effectively suppress weeds. In addition to reducing seedling emergence, residues may also delay emergence and allow the crop to gain an advantage over weeds and reduce the need for control. Mulches, however, tend not to suppress weeds completely and therefore their use needs to be integrated with measures such as postemergence herbicides.

There are many gaps in our understanding of the factors influencing weed emergence and survival. Greater knowledge of the role these factors play in determining weed establishment and how they differ between species could greatly improve the effective application of current practices, and contribute to the development of novel weed management strategies.

Insect management methods

Insect pest management in rice requires a broad ecological approach that includes biological, cultural, and occasionally chemical control combined with insect-resistant rice varieties (Heinrichs 2007). Naturally occurring biological control with indigenous predators, parasitoids, and insect pathogens is critical to rice insect management (Way and Heong 1994). These indigenous natural enemies have worked for thousands of years. They will be more important in the future than they have been in recent years, during which insecticides have often destroyed them. Unless destroyed by chemicals, predacious spiders are abundant in the field and attack all stages of rice insects. For example, the wolf spider, *Pardosa pseudoannulata*, is an important predator of brown planthopper, with one spider eating up to 45 hoppers per day (Heinrichs 2007). Because of the extensive use of insecticides, these spiders and numerous other predators and parasitoids have been suppressed and brown planthopper, a secondary pest, has become serious in many locations (Heong and Schoenly 1998, Heong 2009).

Numerous parasitoids attack the eggs, larvae, and pupae of the rice leaffolder. And, pathogens belonging to the fungi, bacteria, and virus groups play an important role in regulating rice insect pest populations (Heinrichs 2007). Many cultural practices can potentially control rice insect pests, such as (1) mixed cropping, (2) varying the age of seedlings at the time of transplanting, (3) water management, (4) fertilizer management, (5) crop rotation, (6) the number of rice crops per year, (7) planting time, (8) trap crops, (9) tillage practices, (10) weeding, and (11) synchronous planting, among others (Heinrichs 2007). Chemical use should be contemplated only when an insect pest is proven to cause loss (Way and Heong 1994).

IRRI is attempting to develop ecological engineering methods to strengthen natural enemy biodiversity that are fundamental to increasing biological-control ecosystem services to regulate pests. The prospect of using ecological engineering in rice was discussed by Gurr (2009). This work is being undertaken in China, Thailand, Malaysia, and Vietnam using methods such as increasing beneficial plants along bunds to provide food sources for the natural enemies and improving timing of sowing to avoid invasion of pest vectors carrying virus diseases (IRRI 2009). Plants under attack by pests often produce volatile chemicals that attract natural enemies (Bruce and Pickett 2007). These herbivore-induced plant volatiles (HIPVs) have been synthesized and used as sprays to obtain elevated biological control activities, suggesting that HIPVs can be used to attract natural enemies to crops (Gurr 2009). Lu et al (2006) found that rice plants attacked by the brown planthopper attracted more egg parasitoids.

As discussed above, there is potential as well to achieve varietal resistance to insects through biotechnology. *Bt* rice for stem borer control is one example, but there are others as well. The use of MAS for speeding up the development of varieties, such as ones with resistance to brown planthopper, is another example. MAS may be a more important solution to speeding up the development of varietal resistance than GMOs, at least until the regulatory and market constraints for the latter are resolved. Climate change may increase the demand for water-conserving varieties, and also for varieties with improved insect tolerance as ecosystems evolve with global warming.

In the foreseeable future, insecticides will remain the dominant tools farmers use in their fields. It is risky and expensive, costing $256 million, to research, develop, and register a new crop protection product, and only 1 in 139,000 chemicals make it from the laboratory to the field (Croplife America 2010). Chemical companies are likely to focus on developing new chemicals with novel properties, such as buprofezin and the neonicotinoids, selective modes of action (Ishaaya et al 2007), and new delivery systems, such as nano encapsulation of imidacloprid (Guan et al 2008). However, their proper and sustainable use in rice fields will depend on farmers' knowledge, equipment, access to the novel technologies and well-balanced advice, good product stewardship programs, and well-managed regulatory and marketing structures. Rice planthoppers have developed multiple layers of resistance to the neonicotinoids introduced in some countries about 10 years ago because of excessive use (Matsumura et al 2009). Buprofezin, a product noted for its selectivity to planthoppers, is often not available or not recommended to farmers by rural pesticide dealers because of its higher cost and delayed mortality effects. Some companies institute good stewardship programs to ensure safe and proper use of pesticides, but others do not, and they exploit the market and prey on farmers' lack of knowledge, thus exacerbating pesticide misuse.

Disease management practices

Successful rice disease management begins with varietal resistance as a base because it is the simplest and cheapest way for farmers to manage disease. For many diseases, once an epidemic develops in a rice crop, the spatial-temporal pattern of epidemics (many fungi and bacteria, most viruses) and the injury-crop loss relationships (Savary et al 2006a) may easily lead to difficult management. Resistances to diseases can, in several diseases, be overcome by pathogens, and so new resistances are needed every few years. In addition, if environmental conditions are highly favorable for a disease such as blast, or if new pathogen races occur, epidemics can be triggered on previously resistant varieties (Teng 1994, Leung et al 2003, Wopereis et al 2009). Therefore, other control methods can be combined with varietal resistance, including (1) choose crop establishment dates that do not coincide with environmental conditions that are conducive to disease intensification, (2) synchronize sowing or transplanting to prevent green bridges that favor disease transmission across crops, (3) use healthy or treated seed, (4) reduce the sources of primary inoculum, (5) use proper plant nutrition, and (6) use genetic diversity through varietal rotation, varietal mixtures, intercropping, and crop rotation (Zadoks and Schein 1979, Teng 1994, Croplife Asia 2004).

Because of the fundamental importance of varietal resistance to disease management in rice, disease control is a strong target for molecular techniques. The use of MAS for speeding up the development of varieties with resistance to bacterial blight, tungro, and blast is an excellent example (Jena and Mackill 2008).

Preventive or curative chemical use is usually not desirable. Unfortunately, for some diseases for which (1) no effective resistance exists and (2) epidemics are relatively slow and strongly aggregated, fungicides combined with crop management may offer efficient options. Seed health management—the securing and processing of seed lots that are specifically harvested and stored for crop establishment—is a key element to prevent seed-borne diseases (Mew 1991).

Rodent pest management

In the 1960s, a wide range of chemical rodenticides became available on the global market. However, despite the development of a new generation of chemicals in the 1980s, rodents developed tolerance of most of them. There are also serious concerns over their humaneness, and their impact on nontarget species. Ecologically based rodent management, or EBRM (Singleton 1997), has now taken center stage for rodent control in Asia, Australia, and eastern Africa (Stenseth et al 2003, Singleton et al 2007). In Southeast Asia, EBRM has been particularly effective in intensive lowland rice agroecosystems, leading to acceptance of EBRM by smallholder farmers (Singleton et al 2005).

IPM delivery approaches

The fundamental question for the future of rice pest management is how to achieve widespread use of IPM alternatives to manage rice pests with minimal use of pesticides, minimum externality costs, high yield, and high profitablity. Many scientists argue that IPM practices are currently available to manage most important rice pests in an economically viable manner with few if any pesticides, although improved IPM practices are continually needed given (1) the dynamic nature of pest populations, (2) increasing labor costs, and (3) new and aggressive marketing strategies of the pesticide industry. Unfortunately, the efficacy of rice IPM is currently hindered by the excessive use of chemicals that destroy ecosystem services that regulate pests, and approaches used to encourage reducing unnecessary pesticide use have not resulted in widespread farmer adoption of IPM. The question is how to achieve that adoption.

Some aspects of pest management, such as weed management in direct-seeded rice, are “knowledge-intensive,” and as such improving the availability of information is a prerequisite for sustainable weed management (Rao et al 2007). Changes in weed flora are likely and the provision of relevant information to support decision making is essential for appropriate management responses. Such information, however, is often not available to farmers.

Some argue that adoption of IPM is already widespread because most farmers currently plant improved rice varieties with at least some pest resistance and many farmers also hand-weed. However, most definitions of IPM include not only the use of multiple types of pest management practices, but also synthetic chemicals are used only when essential. Therefore, most would say that the majority of farmers currently apply too many insecticides and fungicides to fit the definition of their having adopted IPM. Pest-resistant varieties are clearly not fully appreciated by farmers, as pesticides are still being used to treat the same pests for which the varieties are said to be resistant.

If IPM is indeed more economically profitable with lower pesticide use, then one must ask why pesticides are still the preferred option for most rice farmers. One answer is that adoption of any pest management practice depends on farmers (1) being aware of its existence, (2) perceiving that it will benefit them if it is adopted, and (3) finding it available and understanding how to use it. Pesticides meet all three requirements. Most pest-resistant varieties do as well up to a point. However, many types of cultural and biological controls for pests fall short on the second and especially the third requirement. They are information-intensive, and in some cases even require coordination among farmers in an area. Therefore, IPM information must reach farmers though intensive delivery approaches such as FFS or the information must be simplified to facilitate its understanding by farmers.

Several other factors hinder IPM diffusion. First, governments often find ways to directly or indirectly subsidize pesticides and create roadblocks to the approval of nonchemical practices. Second, many IPM practices that scientists or even farmers develop address only one specific pest at a time. Therefore, farmers may apply chemicals for others pests, thereby defeating the efficacy of the first practice or facilitating secondary pest outbreaks. Now, let's take a look at how each of these problems can be overcome.

The issue of governments subsidizing pesticides requires a concerted effort to educate and modify the attitudes of plant protection officials and policymakers who decide about pesticide policies and regulations, the problems associated with pesticide use, and the benefits of IPM (Heong 2009). Plant protection officials, public extension agents, and even credit officers are often placed in situations where they understand the problems of farmers using pesticides, but they must follow the rules and regulations favoring chemical use that were established by higher-level policymakers. They tend to use procedural or political reasoning in their decision making. Examples of policies or rules that require chemical use are the government distribution of free or subsidized pesticides during a pest outbreak, or a requirement for farmers to have pesticide plans to obtain credit. An example of a policy roadblock to nonchemical use is a requirement for long and expensive testing for a biological control product to be approved for release or import even if that product was already found safe in countries with extensive testing procedures. This is especially important to prevent extension staff from becoming formal or informal sales persons for pesticides (Matteson 2000).

In some cases, scientists from the public sector also serve as consultants to pesticide companies, creating a potential conflict of interest.

The issue of farmers attempting to adopt one or a few IPM practices while still applying chemicals for most of their other pest problems is a concern. This would seem to argue for the widespread use of FFS, but public budgets are insufficient to reach very many farmers with such an expensive approach. The existing estimates of 2–3 million farmers having been reached with FFS after two decades means that only a tiny fraction of producers have been reached. In addition, the turnover of farmers and discontinuance may erode the effects (Escalada et al 2009). The simple rule or heuristic approach such as "Do not spray rice for the first 40 days" reached more farmers and reduced chemical use to a greater extent (Heong et al 1998), but was not comprehensive enough to cover all aspects. The follow-up campaign of "Three Reductions, Three Gains" was a stronger step in the right direction (Huan et al 2008). Although it may not be as information-intensive as FFS, it integrates the messages of the importance of appropriate plant fertilization, fewer but higher quality seeds, and reducing the use of pesticides. Importantly, the three reduction message could be spread through a variety of mass media, including radio soap opera, to reach more farmers (Heong et al 2008).

The media approach alone, however, is not sufficient to communicate all important messages to farmers, especially if a message is complex and if there are problems that farmers may not recognize. And, the knowledge and ideas that farmers have will not be built upon. That problem could be addressed through integrated IPM research and delivery programs that include demonstration sites that are strategically placed and linked to research and extension. Sites for FFS programs could coincide with some of these demo sites, although the sites would function for a longer period of time than an FFS course. At the demo sites, farmers would be integrally involved with the scientists in testing IPM practices, providing feedback, and experimenting on their own.

Active research is needed in each rice-growing country on the most effective mass media approaches. Although some basic approaches such as radio messages, posters, and leaflets are suitable at most sites, others such as TV dramas and plays may work only in specific areas. Modern communication technology is evolving rapidly and is likely to present new mass media opportunities. An important aspect of using mass media is to figure out how to simplify an integrated set of practices into a message that still has enough information content. To the extent that various delivery mechanisms can transmit information repeatedly on similar packages through different but complementary means would improve the chances of widespread and sustainable success.

One of the reasons that pesticides have been so popular is that the private sector can make a profit off of them and therefore it has an incentive to market them. To the extent that some of the components of IPM packages can be distributed (sold) through small or large private entities, the chances of widespread distribution would increase as well. In some cases, it may be possible to use the pesticide company tactics and allow scientists or even extension workers to receive commissions for their involvement with private entities. In addition, IPM researchers and practitioners need to learn about marketing principles and develop more appealing ways to extend (or sell) IPM.

IPM in schools is another complementary but underused delivery strategy. By preparing IPM educational materials that can be used in schools, the awareness and perception requirements mentioned above can be met at a modest cost on a widespread basis. Teaching children about ecological principles before they are tempted to use pesticides would help even the playing field. One of the keys to implementing a school IPM program is to work to have it mandated from the top of the educational system. A good example is provided by the Pennsylvania School IPM program in the United States (Pennsylvania State University 2009).

Ecosystem approaches

Despite ecology having increasingly been emphasized since the 1960s, the concepts of "ecosystem" and "ecosystem management" approaches to IPM are yet to be truly implemented (Maltby et al 1999). Awareness has been growing, however, of the importance of "ecosystem services" to human welfare and that the world's poor have a disproportionate, direct reliance on these ecosystem services (MEA 2005). In maintaining ecosystem services, biological interactions are important (e.g., the relation of predators and prey), and biodiversity has an important role in regulating ecosystem services, such as pest and disease regulation and pollination (UNEP-WCMC 2007). Biodiversity describes the abundance and diversity of genes and species, ecosystems, and habitats within a region and, in the context of pest buildup, the roles of many species in the landscape are poorly understood. Such interactions have been recognized, for example, in the relations between natural enemies and the dynamics of insect pests in rice, but they have not been broadly applied to other pests. Studies have been undertaken to record the response of weed flora to crop management (e.g., Man and Mortimer 2002, Singh et al 2008) and to determine the factors that influence establishment and growth (e.g., Chauhan and Johnson 2009b). Such studies, however, involve very few species and do not consider how changes in one population may affect another. More understanding of interactions within the ecosystem is needed to be able to anticipate undesirable changes. Further, greater research efforts are required to provide more precision in predicting undesirable changes in weed flora, and in how to address these changes with appropriate management practices and decision tools.

Summary and conclusions

Rice pest problems are serious but, ironically, at least for insects, have been worsened by many of the pesticide applications designed to address them. Recent BPH outbreaks in China, India, and Thailand are examples of secondary pest problems that have become primary pest problems as a result of excessive chemical use. Such insect outbreaks have also caused viral epidemics, with serious consequences. As labor costs continue to rise, especially in Asia, where 90% of all rice is produced, herbicide use is also expected to increase unless new improved alternatives for weed control are developed and adopted. The misuse of pesticides has resulted in acute and chronic health problems with eyes, skin, and respiratory, cardiovascular, and neurological systems. Pesticide use has affected the number of species in rice paddies, relative composition of species, and residue accumulation in surviving populations. Several off-paddy effects occur as vertebrates accumulate pesticide residues.

Pesticide use on rice has leveled off in recent years, and the change in types of active ingredients applied toward ingredients that are more environmentally benign represents progress. Given the cost of registering new chemicals today, it is possible that the tide will swing more toward other IPM practices in the future. For many diseases, host-plant resistance represents the cornerstone of IPM, and maintenance breeding, enabling rotation of new resistance genes, is a critical element for the future. Marker-assisted breeding—and its widespread use in rice-producing countries—represents a key advance and should reduce costs in this area. However, forces are also at work that may hamper IPM implementation and increase pesticide use in the future without solving pest problems. Unless there is sufficient research on IPM alternatives, improved IPM delivery methods designed to achieve widespread IPM dissemination, continued tightening of pesticide regulations and enforcement, and improved policies, these forces may prevail.

Pesticide data trends indicate a long way to go to achieve widespread adoption of ecologically sound pest management. Some progress has been made, but more and faster changes are essential for sustainable rice production systems. A concerted effort is needed that focuses on policy, research, training, and communication approaches. The following actions constitute important elements of this concerted effort:

1. Enlightened pest management policies and regulations are needed. These can be facilitated by programs and processes that engage policymakers in dialogue to modify their perceptions. All subsidies for synthetic pesticides should be abolished and registration processes for bio-pesticides and pheromones should be simplified. Crop insurance mechanisms should be encouraged where practical as one problem is that farmers apply pesticides as "insurance" against crop losses.
2. Research support is needed for a wide range of IPM components that include host-plant resistance as well as cultural and biological control methods. Biotechnology opportunities for developing host-plant resistance to pests should be explored as well and scientifically based regulatory processes refined. Fortunately, significant research efforts are under way to develop and refine IPM component technologies. The key will be to have a complementary set of cost-effective delivery approaches that can be implemented in a widespread area.
3. IPM research and delivery methods must rely on a combination of approaches that include (a) mass media transmittal of simple messages that focus on practice clusters such as the "three reductions" message, (b) on-farm research that links farmers and extension workers to researchers, (c) substantial private-sector involvement, and (d) IPM in schools.
4. Pesticides are likely to remain important tools in rice pest management for many years, but an integrated approach is needed that can reduce reliance on

pesticide applications, lessen the risk of resistance, and slow the change in pest composition. To the extent that pesticides are part of the IPM toolbox for pests, the focus should be on new-generation selective, low-toxicity pesticides, biopesticides, and improved application technologies.

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Notes

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Emerging technological and institutional opportunities for efficient postproduction operations

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Introduction

In 1983, Wimberly (1983) cited in the introduction of his IRRI-published "Technical Handbook for the Paddy Rice Postharvest Industry in Developing Countries" the magnitude of postharvest losses, ranging from 7% to 25%, and called for continued research and development in the postharvest industry. Today, almost 40 years later, Wimberly's book rates among the top five downloads of IRRI publications at Google Books, indicating that, despite previous improvements in the postproduction chain, continued efforts in postproduction R&D are urgently needed.

Postproduction in this chapter refers to all operations needed to move rough rice from the field to the market in milled rice forms. This starts with cutting and collecting the crop from the field, threshing it to remove and separate the grains from the straw, cleaning the threshed rough rice, drying rough rice to safe moisture content, storing rough rice, removing the husk and the bran (milling), storing the milled rice, and marketing.

Probably the biggest success story of postproduction R&D in rice is the axial-flow thresher (AFT). Developed from 1970 to 1972 at IRRI (Khan 1985), the axial-flow threshing principle is now being used all over Southeast Asia and in other parts of the world. Locally produced AFTs in the Philippines and Indonesia range from small portable machines with only a threshing drum to large units on wheels equipped with cleaners. Small to large combine harvesters using the AFT principle are being used in Thailand, China, Cambodia, and Vietnam. IRRI's USAID-funded *Small Farm Machinery Development Program*, under which the AFT was developed, had managed to address a clear need for mechanized harvesting to reduce turnaround time, which allowed farmers to produce a second crop using modern early-maturing varieties introduced during the Green Revolution.

But, despite decades of continued postharvest research and development by international and national research systems, the postharvest sectors in Southeast Asia are still characterized by high postharvest losses. FAO estimates these losses to be 15–50% (Mejia 2004). They consist of a 15–25% loss in weight through spillage, losses to pests, and low milling yields. In addition to these physical losses, inappropriate postharvest management practices, delays in the postharvest chain, outdated postharvest equipment and infrastructure, and low operators' skills lead to losses in quality along the chain, which often reduces the market value of milled rice by 10–30% or more. Farmers are also often forced to sell immediately after harvest at a low price and therefore they lose out on maximizing their returns.

This chapter assesses the major developments of postharvest technologies from harvesting to milling and highlights current trends, with a major focus on the countries in Southeast Asia. This is followed by an elaboration of new approaches that have shown potential to increase the impact of postharvest R&D. The chapter concludes with an outline of future R&D needs considering the above driving factors.

Transitions in postharvest systems

The challenges to reduce losses and enable farmers and processors to maximize their returns from the rice harvest remain. Improved postharvest management options and technologies need to be researched, developed, adapted to local conditions, and made available at affordable cost. This needs to take into account the following factors that drive the transition of the rice value chain from simple to more advanced postproduction systems:

1. Increasing intensity of land use and an increased number of crops per year, which results in more crop for processing during the harvest season and, when double cropping is introduced, often additional harvesting operations during the wet season. Because of the increased volume to handle and process and shorter turnaround time, increased quantitative and qualitative losses can occur in existing postharvest systems.
2. The mode of rice production for subsistence, local markets, or high-value export markets, or a combination of these.
3. Increasing quality consciousness in local markets and newly developing niche quality markets for higher-value products.
4. Increased labor cost and delays in postharvest operations caused by labor scarcity.
5. Institutional changes, with an increased role of the private sector in R&D and in the provision of extension and services.

Figure 1 shows a framework for assessing how factors 1–4 affect the level of technology in the postproduction chain using three examples, harvesting, drying, and milling. In Figure 1, labor availability for postharvest operations is represented on the vertical axis and the market orientation of rice farmers on the horizontal axis. The two-by-two typology displayed helps understand the cross-sectional variations in the nature of postharvest technologies across countries. It also provides the possible transitions over time that are likely to occur as the extent of labor availability and market orientation change in the course of economic development.

Mechanization of harvesting is driven mainly by the shortage of labor. On the other hand, dryers usually get introduced to reduce quality losses and only secondarily to reduce the labor requirement for sun drying. Figure 1 also shows that more complex and knowledge-intensive technologies enter the postproduction system with increases in the demand for grain quality and with a labor shortage. The history of mechaniza-

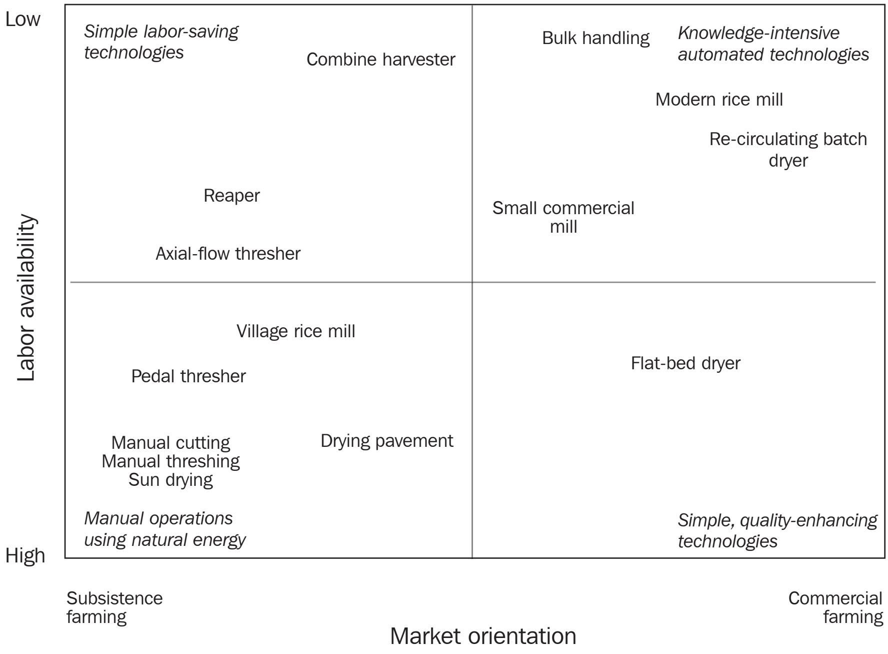

Fig. 1. Factors driving postproduction development and development stages of selected technologies for harvesting, drying, and milling.

tion also teaches us that usually power-intensive operations such as threshing get mechanized first and knowledge-/skill-intensive operations such as cutting the crop with a reaper follow later.

In Cambodia, with its low population density and lack of established market channels for quality rice, the major issue today is the increasing labor shortage. Farmers are therefore experiencing increasing labor cost and delays, and high losses in harvesting. Consequently, within a few years, combine harvesting has been introduced and is increasingly being used in contract-harvesting schemes. In Vietnam, which became a major rice exporter in the 1990s, flat-bed dryers have been introduced successfully in the Mekong Delta to ensure better quality of rough rice.

The types of partners and the nature of partnership with various agents in postproduction systems also tend to change with a change in technologies. These partnerships are likely to evolve from simple informal arrangements to complex business arrangements (Fig. 2).

Replacing manual threshing with a simple machine often requires only two partners, the contract service provider and the farmer. The more technically complex combine harvesters require additional training provided by manufacturers or the extension service. A rice-drying service for farmers requires additional partners to ensure access to quality markets. Even more complex partnerships are needed if a rice mill

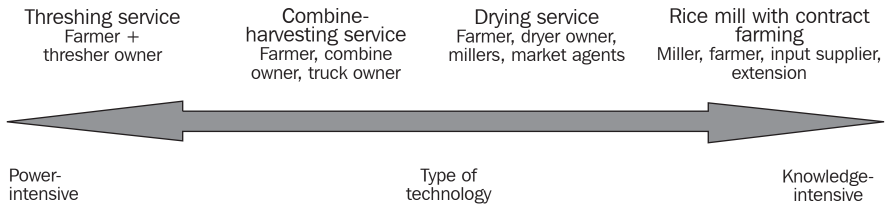

Fig. 2. Relationship between required partnerships and the application of postproduction management options of different knowledge intensiveness.

engages in contract farming to ensure optimum quality rough rice as a raw material for the mill. The miller then needs to link to providers of good-quality seeds and other inputs, to extension services for the contract farmers, and possibly to services for land preparation, harvesting, and threshing.

Postharvest operations, losses, and quality

Typical losses in traditional postproduction operations in Southeast Asia can reach 1–5% in cutting and handling, 1–5% in manual threshing, 3–5% in sun drying, 5–10% in traditional storage, and 20–30% for village milling. Given the annual rice production in 2008 for Cambodia of 6.8 million tons, the Philippines (16.8 million tons), and Vietnam (35.9 million tons), a 5% reduction would mean that in 2008 Cambodia could have increased its exports by 68% while Vietnam could have exported 26% more. Thus, both countries would have contributed more to ensuring the global rice supply and keeping the global rice price at an affordable level for most poor consumers. The Philippines, on the other hand, could have reduced its imports of 1.8 million tons in 2008 by 0.59 million tons, or 33%. All three countries together would have provided roughly 2 million tons more of milled rice to the world market.

The quality of rice is influenced by variety, preharvest environment, and postharvest handling. The quality of grain is best when it reaches physiological maturity in the field. Optimum postproduction management from that point forward has the objective to minimize any decline in quality. The following major factors affect quality during postharvest operations:

- Moisture content (MC):Rice is harvested between 18% and 24% moisture content and should be dried within 24 h for safe storage levels, which are below 14% (on a wet basis) for grains and below 12% for seeds. Rough rice with high MC heats up quickly from respiration and offers ideal growing conditions for molds and insects. Harvested dried grains need to be protected from absorbing water from the surrounding air—any re-wetting of grains leads to cracks developing in the kernel.
- Timeliness of operations: Harvesting before optimum maturity results in very wet rough rice and low yields, while delayed harvesting increases shattering loss and cracked grains. Delays in drying result in a rapid deterioration in quality.

Reports from Asian market surveys have found significant levels of mycotoxins in locally marketed rice. Recent research indicates that delays in postharvest operations can cause high levels of mycotoxins (Gummert et al 2009).

- Storage pests, such as rodents, birds, insects, and pathogens, cause high damage and losses through a combination of feeding, spoiling, and contamination of both rough rice and milled grain. Singleton (2003) summarized losses caused by rodents in production and postproduction and found only a few data for postharvest losses such as estimates for India amounting to 25–30%.
- The type and maintenance status of postharvest equipment and machinery not only determines the amount of physical losses but also quality loss such as damaged grains in threshing and harvesting machines, overheated grains with discoloration or loss of germination in dryers, hot spots and molding in storage, and excessive broken grains in milling.

Technical status and current trends in postharvest technology

Mechanization of the postharvest sector is essential to reduce losses and improve grain quality. This section outlines the technical developments in the different postharvest operations in Southeast Asia.

Harvesting

The goal of good harvesting is to ensure maximum grain yield by minimizing grain loss and preventing quality deterioration. Harvesting systems vary from region to region and include different methods for harvesting, hauling, threshing, and cleaning. In subsistence and small-scale farming systems, these operations are still often carried out manually. Around 10–15 person-days are required for manual cutting, while 5–7 person-days are needed for manual threshing; losses in manual systems can reach 7–20% depending on the season and local practices (Bautista et al 2007). Harvesting cost on average is between 15% and 20% of rough rice value.

During the Green Revolution, increases in production through varietal improvements, better management, and new double-cropping systems resulted in more crop to be harvested, which led to the successful introduction of the axial-flow thresher throughout Asia (Khan 1985). Local manufacturers made many modifications to the original design and produced different machines from small portable threshers with cleaners (Fig. 3A) to large truck-mounted threshing units. In the intensive rice systems, around 80–100% of threshing is now mechanized. A second push for mechanizing harvesting came about in the early 1990s in Thailand's Central Plains as a result of labor shortage. Thai manufacturers then developed the first local combines with 3-m cutting width using an AFT initially mounted on secondhand track drives (Krishnasreni and Kiatiwat 1998). Today, a flourishing combine manufacturing industry has developed with five manufacturers having an annual production capacity of 800–1,000 units (Kanuengsak Chiaranaikul 2009). Machines are also being exported to neighboring countries (Fig. 3C). In Punjab, India, several manufacturers produce large conventional combines with straw walkers, which in some areas harvest almost

Fig. 3. (A) Axial-flow thresher in Vietnam; (B) mini combine harvester in Cambodia; (C) Thai axial-flow combine harvester.

all of the nonbasmati rice. In 2009, there were an estimated 3,000 combine harvesters and 3,600 reapers in the Mekong Delta with capacity to harvest around 15% of the total rice-growing area (Phan Hieu Hien, personal communication). In Indonesia and the Philippines, the number of combine harvesters is still marginal because of smaller plot sizes and little quality differentiation in their markets.

Addressing the need for small-scale combines in the Philippines, Vietnam, and other Southeast Asian countries, a mini-combine able to harvest around 1 ha per day was developed in a public-private partnership between Philippine Rice Research Institute (PhilRice) and Briggs&Stratton (B&S) (Fig. 3B). Around 700 machines were produced by Vinapro in Vietnam until 2009 and several units were even sold to Africa. After demonstrations in Cambodia and Lao PDR in 2007-08 (Gummert 2007), demand for combine harvesters increased in these countries, resulting in machines from Thailand, China, and Vietnam now entering their markets.

Small-scale stripper harvesting systems, which only comb grains from stalks and leave the straw standing in the field, were piloted throughout Southeast Asia (Tado et al 1998) but got adopted only in South Sulawesi, Indonesia, where different models of stripper harvesters with 600–1,200 mm of working width (Chandue 2005) are produced for local markets.

Drying

Although most of the quality losses in postharvest could be prevented by timely and proper drying, the use of mechanical dryers throughout South and Southeast Asia is very limited. In the Mekong River Delta of Vietnam, which has the highest penetration of dryers in the Greater Mekong Subregion (GMS), the installed dryer capacity can cover only 30% of the wet season harvest (Truong Vinh et al 2009). In the Philippines, Lao PDR, Cambodia, Myanmar, and Indonesia, national dryer capacity is negligible. Most farmers and many processors still rely on traditional sun drying despite quality losses because the markets of these countries don't offer a significant quality incentive for mechanically dried rough rice.

Most attempts to develop and introduce farm-level dryers have therefore failed. Vietnam was different because, in the Mekong Delta in the 1990s, farmers had problems drying their rough rice because of a lack of roads and millers' reluctance to buy wet rough rice. A low-cost dryer based on traditional storage containers made from circular bamboo mats as shown in Figure 4A therefore gained widespread usage (Ban et al 1995). It consisted of a bamboo bin, an additional central duct, a small axial-flow blower, and either an electric heater or a coal furnace to move heated air through the bin. It costs less than US$100, which was affordable enough for around 1,400 farmers (Phan Hieu Hien 1999). Since flat-bed dryers (FBDs) were already introduced in the 1980s and were used by contract service providers, the low-cost dryers dried less than 2% of the mechanically dried rough rice but they helped popularize mechanical drying.

Because mechanical drying results in higher head rice yield (Bhandari 2007) and better milled rice quality, it is usually the miller who gets the financial return from mechanical drying. Rice millers, traders, or drying contract service providers also handle the amounts necessary for a good annual use of the machine. Most dryer installations are therefore found at this level. Only a few large-scale and often export-oriented rice mills use Western-type re-circulating batch dryers (Fig. 4C) or continuous-flow dryers. Medium-size rice mills use locally produced or imported re-circulating batch dryers with 6–10-ton capacity or simple locally produced FBDs with 4–10-ton capacity (Fig. 4B). Many sophisticated dryer designs have failed because of high energy cost, lack of after-sales services, and lack of market incentives for quality.

Advanced drying systems such as two-stage drying—with fluidized bed dryers or heated-air flash dryers as the first stage and in-store drying as the second stage—were piloted in the Philippines, Thailand, Vietnam, and China. In Thailand, around 100 rice millers bought fluidized bed dryers and 50 rice mills installed in-store dryers while in China improvements in existing bulk storage systems were made (Srzednicki and Driscoll 2008). In the Philippines (Chupungco et al 2008) and Vietnam (Phan Hieu Hien, personal communication), the two-stage system was introduced in the 1990s but was not adopted by users.

Despite its high labor requirement and some compromise on grain quality, the FBD has proven to be an appropriate technology for shifting from traditional systems toward mechanized drying. It was developed by the University of the Philippines in

Fig. 4. (A) Low-cost farm-level dryer in Vietnam; (B) reversible air-flow batch dryer with 4-ton capacity with rice husk furnace in Vietnam; (C) re-circulating batch dryer at PhilRice, Philippines.

Los Baños (UPLB) in the late 1970s, with a capacity of 1–2-ton and piloted in most Southeast Asian countries, with limited initial success. In the 1990s, the University of Agriculture and Forestry (UAF) in Ho Chi Minh City successfully introduced the dryer in Vietnam and helped manufacturers to upscale the technology to 4–10-ton capacity. More than 6,200 units were installed in the Mekong Delta by 2008 (Phan Hieu Hien 2008). Starting in 2005, IRRI had then collaborated with national agricultural research and extension systems (NARES) and with local private sector partners in transferring the technology to Cambodia, Myanmar, and Lao PDR , where no rice dryers were used yet. By 2009, users had bought more than 48 locally produced dryers in Myanmar (Kyaw 2008), 12 in Cambodia, and more than 10 in Lao PDR, with increasing trends. A similar dryer is now being adopted in South Sumatra in Indonesia (Bhandari 2007). In the Philippines, an FBD with 4-ton capacity based on the Vietnamese design was introduced by PhilRice and UAF (Gagelonina et al 2001). Reasons for the successful introduction of the FBD included foremost the shift toward more export market-oriented production, which requires higher quality (Fig. 1); but also local adaptations based on users' feedback; inclusion of the private sector; simplicity of the technology, which does not need an after-sales network; and reasonable drying and investment cost.

Storage

Despite many efforts to introduce bulk handling and storage for rice (Champ and Highley 1987), around 80% of world rice production is still handled and stored in bags. Keeping dried grains and seeds safely in humid tropical conditions requires protecting them from high humidity during the wet season, pests, and mycotoxin infestation. This remains a major challenge both at the farm level and in the commercial sector. Seed stored on the farm usually loses its ability to germinate after a few months. In Lao PDR, Myanmar, and Cambodia, and in the subsistence-oriented production systems of other countries, farmers store rough rice in granaries and in bags for own consumption or for sale after prices rise in the off-season. In the intensive systems in the Philippines, Indonesia, and Vietnam, farmers sell most of their rough rice immediately after harvest either because they are indebted and have to pay back loans and want to avoid the risk of losing quality or because there is no significant seasonal price difference. This is the case in India, where the rice price is government controlled. Improving storage can help farmers minimize risk, reduce losses, and maximize profits from selling at a higher price.

Hermetic storage involves enclosing the grains in an airtight container, thus minimizing gas and moisture transfer from the ambient air and protecting the grains efficiently from water adsorption, pests, and fungi. Biological activity reduces oxygen inside the container to below 5% (Fig. 5C), which provides efficient insect control. Commercial systems (Cocoons™) with 5–200-ton capacity (Fig. 5A) were first evaluated in the Philippines in 1991 and by 2004 around 353 cubes with 5–15-ton capacity were used by Philippine government agencies. Participatory technology verification with farmers since 1999 identified the need for smaller systems and led to the development of the 50-kg hermetic Super Bag (Rickman and Aquino 2004) (Fig. 5B). Piloting of Cocoons and Super Bags with farmers and millers in 12 villages in Cambodia and

Fig. 5. (A) Hermetic Cocoon with 5-ton capacity, formerly marketed under the name Volcani Cube; (B) farmer in Laos with seeds in a hermetic IRRI Super Bag with 50-kg capacity; (C) oxygen concentration in Super Bags with different oxygen permeability.

Vietnam between 2006 and 2008 and smaller participatory trials in Lao PDR, Myanmar, and Indonesia (Mendoza 2007) showed that hermetic storage maintains MC, controls insects efficiently, maintains the germination rate of seeds above 90% even after 9–12 months of storage, and results in less broken grain in milling and thus higher head rice recovery, typically between 2% and 10% in 9 months of storage (Ben et al 2006).

In Bangladesh, farmers learned to convert their own clay pots, plastic containers, or metal containers into hermetic storage systems for seeds by sealing them airtight (Taher Mia et al 2008). In Sri Lanka, hermetic concrete storage bins were developed for the farm level and tested successfully (Adhikarinayake et al 2006).

The advantages of hermetic storage are convincing and several multinational and local rice seed producers now store their seeds in hermetic systems (Villers and Gummert 2009), and hermetic storage systems are used by the private sector for other crops such as cocoa, wheat, pulses, and maize. It took roughly 20 years from the first testing of the Cocoons to the significant usage of the Super Bag.

FAO has developed metal silos and, with funding from various donors, has advised manufacturers and disseminated the technology to farmers in 16 countries (FAO 2009).

Bulk handling and storage are used only by some advanced rice mills and processors. Limiting factors are the large-scale structural adjustment with high investments needed and technical problems related to the hot humid climate. R&D objectives for storage should nevertheless include the introduction of bulk handling and storage systems to minimize losses along the value chain (De Padua 1999).

Milling

Rice milling is the process of removing the husk, the germ, and the outer covering of the endosperm (bran) with the objective of producing a maximum amount of milled rice with minimum brokens. The quality of the rough rice, the type and maintenance status of milling equipment, and operators' skills influence milling recovery (the percentage of milled rice based on rough rice weight) and head rice recovery (the percentage of whole grains based on rough rice weight).

Depending on the scale of production and market requirements, a milling system can be a simple one, a two-step process, or a multistage process. Typically, rice mills in Asia can be broadly classified into three categories: (1) village mills for custom milling, (2) small commercial mills serving mainly local markets, and (3) large commercial mills producing high-quality rice for niche or export markets. In some remote areas, rice is still manually husked by mortar and pestle.

Village rice mills usually have a single machine with capacity of 40 to 300 kg/ha. The IRRI micro-mill represents a variety of the simplest mills consisting of only a steel huller that accommodates husking and polishing in one step. Milling recovery of 50–55% is extremely low, head rice recovery is often less than 30%, and in some countries legislation exists to phase out such equipment. More sophisticated village mills employ two-stage milling machines consisting of a husker, usually in the form of a rubber roller and a steel polisher. This can increase milling recovery to above 60%. Village rice mills usually provide custom service to farmers and villagers and payment is often in kind, for example, by leaving the by-products at the mill as payment. Under those conditions, the miller does not have an interest in improving quality because high losses increase his share of by-products. In Lao PDR, for example, only 8% of the produced rice is sold in the markets; most of the rough rice is milled in village mills.

Small commercial mills process the majority of the rice crop and usually employ specialized machines for cleaning, husking, polishing, grading, and bagging in a multistage process. Capacity ranges from around 0.5–2 t/hour. A large percentage of these mills use old equipment but milling yields are higher than from village mills; in Cambodia, for example, milling recovery and head rice recovery of small commercial mills were found to be 3% and 10% higher than in village mills (CARDI 2000).

Large commercial mills have additional equipment such as de-stoners, mist polishers, and color sorters added to their milling lines. Some have dryers for better control over rough rice quality and, in rare cases, bulk handling and storage facilities. Milling capacities are 2–6 t/hour but can surpass 100 t/hour. These mills produce high quality rice for either niche or export markets and usually use equipment from a few global milling equipment manufacturers. Milling recovery is 65–68% and head rice recovery 50–55%. Since the supply of the mill with sufficient and optimum quality rough rice is important, many of these mills provide extension services to farmers or engage farmers in contract-growing schemes that can also increase profits for farmers (Junning Cai et al 2008).

Other milling systems exist, for example, in Vietnam and in Indonesia, where husking and polishing are often physically separated and/or sometimes also done at different times and at high MC, creating a so-called "two-system" rice milling process. When paddy is husked at high MC (Nguyen Van Xuan and Le Quang Vinh 2009) or the brown rice is stored at high MC, qualitative losses are high. Effective drying systems can help to phase out this unusual practice.

Further investment to replace obsolete or ineffective milling equipment is needed to improve quality in Vietnam (Le Khuong Ninh 2003). Other authors attribute the low quality to imperfect rice market structures, assuming the milling industry would invest in improvements once markets provided quality incentives. Cambodia has too little postharvest infrastructure and currently exports rough rice to Thailand and Vietnam and re-imports milled rice. Investment here should increase milling and storage capacity (Pandey and Bhandari 2009).

By-product usage

Rice has two major by-products: the husk, amounting to around 20% of the rough rice weight; and rice straw, produced in roughly equivalent weights as the grain yield. Although some husk is used for power or heat generation at milling plants, most of the husk is considered waste and, in many countries, is dumped and burned openly. High fossil fuel cost has recently led to the new development of many different types of cook stoves and rice husk furnaces for heating air in rice dryers. Hohenheim University, UAF, and IRRI collaborated to develop an automatic rice husk furnace (Braunbeck 1998). It improves the burning process, reduces pollution and labor requirement in drying (Chandrasekar et al 2006), and is piloted at the commercial level in Vietnam (Phan Hieu Hien 2008).

Myanmar rice millers still use hundreds of rice husk–fired boilers combined with steam engines to power their mills (Dickinson 2009). Rice husk gasifiers coupled with internal combustion engines with nominal power from 20 to 200 kW produced by local manufacturers are commonly used in India and Myanmar and have been imported to Cambodia, where several rice millers installed units. The installed plants still need improvement, especially in waste-water treatment since tar is often released untreated into the environment.

Studies conducted by Haefele et al (2008) indicate that the carbonized rice husk produced by small-scale energy applications through incomplete combustion can improve poor soils but may have little effect on fertile soils.

Rice straw is less used than husk. In India, 23% of rice straw is either left in the field uncollected or, to a large extent, open-field burned. About 48% is open-field burned in Thailand, and 95% in the Philippines (Gadde et al 2009). The remaining straw is used as animal fodder, in mushroom production, and for various other purposes.

A recent study in Vietnam (Phan H. Hien, personal communication) showed that, although about 21 million tons of straw are produced annually, the conversion of straw into power at current fuel price levels is hardly economical. The basic difference in rice straw compared with rice husk lies in its scattered supply. It needs to be collected, pretreated, and possibly stored, causing additional cost compared with husk.

During an expert consultation on biofuels, the use of crop residues, especially rice and wheat straw, was identified as one of the priority R&D areas alongside the examination and sharing of unbiased information on the life cycle performance and impact of biofuel production on food security and poverty (IRRI 2007).

Regional trends

This section describes postharvest status and trends in Africa, which is challenged to become self-sufficient in rice. Cambodia as a country moving toward exports and Vietnam, already a major exporter, are now trying to increase revenues from exports by producing better quality.

Africa

The majority of the rice grown in Africa is produced by small farmers, who grow 0.1–5 ha and depend heavily on human labor to grow and process the crop. The process of cutting, threshing, and transporting the grain is predominantly manual, which requires 50–80 person-days/ha. Grain is stored in 50–80-kg jute or plastic bags either in the house or in granaries outside the house. Rice is normally sold to agents or middlemen at the farm gate, either immediately after harvest or when cash is required. These agents then transport and sell the rice to other agents or millers regionally or, in many instances, outside the country. Farmers normally receive less than 30% of the final sale price for their rice.

In a few western African countries, rice is now being threshed by locally manufactured mechanical threshers. These mechanical threshers originated from the IRRI-designed thresher, which was introduced in the late 1990s and has now been modified for local conditions. Large mechanical combine harvesters have been introduced into many African countries but most have failed because of poor maintenance and lack of product support.

Major losses and contamination occur throughout the postharvest process. Loss estimates range from 15% to 50% of the total crop value. Hand-threshed crops are often left standing in the field until the grain dries down to 15–16% moisture. Optimum harvest MC is 21–22% and waiting until it reaches 14–15% can take more than 30 days. During this time, major losses occur from bird damage, shattering, and weathering. When the crops are manually threshed, the grain is often contaminated with soil and stones. After threshing, farmers tend to allow the grain to dry in bags. Millers often re-dry before storage and processing. When farmers do dry their grain, they normally empty the rice into the bag or, in some instances, lay netting on the ground and then sun-dry. In some cases, they even dry the grain directly on hardened soil pads. Millers and some cooperatives use cement drying pads and very few mechanical dryers are being used. Moisture meters are not used by farmers but are often used by buyers to negotiate quality and price.

Most rice millers now use single-pass mills (250–400-kg/hour capacity), which incorporate rubber rollers for husking and steel polishers. Rubber rollers and sieves are not changed regularly and very few mills have grading facilities. When millers process rice for agents or farmers, they charge on a per weight basis and farmers keep the bran and the husk. Small multistage mills (1 t/hour) that incorporate grading facilities are becoming more popular in some countries, especially where rice is being sold into urban markets. There are still some large multistage mills (5 t/hour) operating from the 1960s and '70s but the volume of supply and availability of spare parts are major constraints in keeping these older mills economically viable.

In many ways, Africa's postharvest sector appears to be at a stage where Asia was several decades ago. Some experiences might be transferable but will require adaptation to local conditions. The Africa Rice Center (AfricaRice) and IRRI are working closely with many sub-Saharan governments, nongovernment organizations, and commercial companies to increase rice production and reduce postharvest losses across the region (Rickman 2009).

Cambodia

Cambodia emerged as a rice exporter in 1995 after it had ceased rice exports for almost 25 years during 1970 to 1995. It is believed that, in 2009, it exported around 500,000 tons of milled rice equivalent, most of it as rough ricethrough informal rice markets to Thailand and Vietnam (Pandey and Bhandari 2009). The Ministry of Agriculture, Forestry, and Fisheries (MAFF) even reported 2 million tons of exports in 2008, with an increasing trend. Government policy aims at re-establishing Cambodia as a major rice exporter and doing value adding through milling inside the country. Despite the impressive increases in production of on average 5.7% per year during 1995-2008, several factors currently hinder the achievement of this goal: (1) infrastructure for postharvest operations such as harvesting, drying, storage, and milling as well as roads and handling facilities are inadequate; several hundred combine harvesters but only a few flat-bed dryers exist; storage facilities are lacking; and around 70% of the total milling capacity consists of outdated village mills; (2) institutional constraints include weak governance, poor coordination, and lack of transparency; (3) poor-quality rough rice as a result of production and postproduction-related problems and subsistence-oriented farmers who don't produce according to market needs; and (4) weak capacity of agricultural extension, service providers, and postharvest equipment suppliers.

Strategies to improve the postharvest sector in Cambodia have to take all these constraints into account and address them along the value chain. Three larger rice mills engage farmers in contract-farming schemes and provide seeds and extension services in order to control the quality of the rice they produce. Several institutions and projects have helped farmers and processors to establish an organic rice value chain targeting markets in Europe and overseas.

IRRI, in collaboration with MAFF and private-sector players, has piloted improved postharvest management options in villages in the six major rice-growing provinces. Continued efforts are needed to outscale improved technologies, enable farmers to have more market-oriented production, and work with farmers and millers on improving quality. This includes support to manufacturers and distributors of equipment; capacity building for farmer intermediaries, farmers, and processors; and facilitating a policy dialog to improve governance and the legal framework.

Vietnam

Vietnam as a country with a postharvest sector in transition toward a quality-oriented export industry is seen as moving with the following trends, especially in the Mekong Delta.

Harvesting became a major bottleneck because of the advocacy of simultaneous rice seeding in the past 5 years. Within 2 weeks, all crops should be established in a province in order to avoid pests such as the brown planthopper. It is anticipated that, within the next 10 years, 80–90% of rice in the dry season will be harvested by combine harvesters. However, in the wet season harvest, due to soft-soil mobility problems in several areas, at least 50% of the rice crop will still be harvested by the two-phase process using a reaper and mechanical thresher.

Mechanical harvesting goes in a pair with mechanical drying. After a transitional period of around 20 years during which some farmers bought dryers, now there is a clear trend toward installing dryers at rice mills, where they are included with storage and milling as part of an integrated system. At mills, dryers will evolve from the current multiunit 8–20-ton-per-batch FBDs to columnar re-circulating or continuous-flow dryers.

As the demand for high-quality rice at a competitive price is increasing on the world market, the rice-processing sector will evolve into an integrated line, from wet rough rice to polished milled rice. The milling equipment now produced by local manufacturers would speed up the change in modernization.

The use of by-products becomes more feasible as more rough rice is processed in a bigger rice mill. Huge piles of rice husks will accumulate and become a nuisance if not disposed of or used properly. The logical way is to convert rice husks into electricity to power the rice mill itself, and sell the surplus power, if any, to the grid. This is in line with the world trend of using renewable energy to replace depleting fossil fuels.

Preharvest operations also influence postharvest losses. Research has shown that leveling of rice fields using laser-controlled equipment (*laser leveling*) results in not only 0.4–1 t/ha higher yield, up to a 25% water reduction, and better weed control (Rickman 2002), but also reduced harvesting losses and better quality from more even crop maturity.

More reduced lodging was observed in Bac Lieu and An Giang of the Mekong Delta on laser-leveled fields than on unleveled neighboring fields. Total losses of rice combine harvesters operating on an upright crop were 1–2% compared with 6–10% in a lodged crop. Thus, well-leveled land can reduce harvesting losses by 5–8%. An Giang Province already planned to level 20,000 ha of rice land.

New approaches for strengthening postharvest impact pathways

Toward the end of the last century, most donors had withdrawn from funding postharvest research because they perceived the previous R&D emphasis on component technologies focused on farm-level problems as having very little impact. New institutional arrangements, business models, and information-sharing mechanisms were needed to develop more relevant technologies and speed up the uptake of R&D results. Several stakeholder consultations through email conferences (De Padua 1998), think tank meetings, and conferences formed the basis for new approaches for increased impact of agricultural engineering (Bell et al 1998), a systems approach for postharvest

(De Padua et al 2000), and improved partnerships (Bakker et al 2000). The outcomes from these processes can be summarized as follows:

- Adopt a systems approach to define the problems and establish priorities;
- Learn to work with other disciplines, particularly socioeconomists, plant breeders, and agronomists;
- Learn to better include end-users of the technology in adaptive R&D;
- Develop cooperative/partnership programs with national research centers, public and private extension systems, and manufacturers; and, finally,
- Realize that not all problems of the industry require new or improved hardware and that, if technology is the problem, multiple sources of technology increase the probability of impact.

In the following years, the IRRI Engineering Unit, NARES partners, donors, and other institutions and programs adjusted their research agenda and included the above recommendations to varying degrees in their planning and program formulation. Mejia (2004), for example, describes the FAO Rice Postharvest System approach, which has been used in several countries, focusing on storage but also on other system components for adding value to rice and its by-products.

Better targeting of interventions

As mentioned in the section on drying, the previous development paradigm, "small postharvest equipment for small farmers," has often failed. The idea of farm-level drying was based on social objectives and ignored the economic conditions farmers were operating in. Given their low production and high cost of equipment, they could not recover their investment. On the other hand, a drying service provided by a small entrepreneur can enable farmers to benefit from mechanical drying at reasonable cost. Although local differences exist, farmers will generally benefit from timely mechanized harvesting and drying services, safe on-farm storage of grains and seeds, value-adding options from rice, improved market information and better understanding of quality traits and affecting factors, and improved village milling. Farmers' groups, cooperatives, and contract service providers usually need assistance in business and organizational management and could be providing drying, harvesting, and storage services with group-owned equipment and also access to marketing channels. Millers who process sufficient volume need improved milling equipment, storage facilities, and dryers suited to the volume processed in their mills, and can provide benefits to farmers through a better price for rough rice or by providing drying services. Financial institutions and policymakers need better information about postharvest to design suitable credit schemes and support policy.

Facilitating multistakeholder platforms

One of the key challenges in improving the impact from postharvest R&D by integration of value chain research and actors lies in the facilitation of processes that enable the various stakeholders from the private and public sector to work toward the common objective of reducing postharvest losses. Participatory approaches, originally developed to embrace farmers in research, can also be used to strengthen multistakeholder innovation systems (Douthwaite et al 2007). Postharvest *Learning Alliances* can help to leverage cross-sector resources, strengthen capacity, and plan, generate, and document postharvest development outcomes. A Learning Alliance can be seen as a process undertaken jointly by research organizations, donors, development agencies, policymakers, and private businesses (Lundy et al 2005). Learning Alliance participants identify areas where diverse interests can be effectively linked for better business outcomes for farmers and other value chain actors. National learning alliances have been established in Cambodia, the Philippines, and Vietnam.

One reason for frustration with the lack of impact in postharvest is that impact, like that of the FBD in Vietnam, was not documented because it often happened long after the projects initiating the technology were completed. Impact assessments therefore were not part of the projects. The Learning Alliance also aims at providing mechanisms to better document the learning and make it available to extension workers, technicians, and, ultimately, farmers through appropriate channels, for example, the Rice Knowledge Bank, an internet-based platform for bridging the research-to-extension gap by capturing research findings that are directly relevant to the extension community, supplemented with training and support knowledge (Shires 2007).

Public-private partnerships

Although a Learning Alliance helps facilitate multistakeholder platforms of rather informal character, more formal partnerships with the private sector are needed for joint R&D to maximize the outcome by drawing on the specific advantages of both sector players. This is especially important since the time when an AFT can be developed by a single institution is over and most of the new technologies for the much more complex environment of the 21st century can often be developed only with partners that have complementary resources and expertise. Most of the technologies that have been successfully commercialized in the last decade constitute such joint developments, often with different roles of the actors in technology development and promotion. The laser-leveling systems, for example, that are now popular in India with 2,000 contractors providing leveling service and are starting to become popular in Vietnam consisted of an existing technology used by the construction sector that was demonstrated and adapted for use in tropical agriculture in collaboration between the manufacturer and public research institutions (Gustafsson and McNamara 1998). The hermetic Super Bag was jointly developed as a new product in a public-private collaboration (Rickman and Aquino 2004), which had a strong research component. Yet another form of public-private partnership for technology transfer and extension is demonstrated by the Myanmar Rice and Paddy Traders Association (MRPTA), which partnered with public-sector institutions to successfully transfer the FBD from Vietnam, start local production, and introduce it to millers and farmers in Myanmar (Kyaw 2008). The aforementioned mini-combine was also one output of yet another type of public-private collaboration. The engine manufacturer B&S supported public-sector research institutions and manufacturers of agricultural machines with the design of the mini-combine and supported adaptive research under the condition that B&S

engines are used in the equipment produced by the local manufacturers. The mini-combine was later successfully localized in partnership with Nong Lam University (NLU, formerly UAF) and a U.S. NGO, ACDI-VOCA (Agricultural Cooperative Development International and Volunteers in Overseas Cooperative Assistance), in the Mekong Delta of Vietnam (Bautista et al 2007).

Issues that need to be examined in this type of collaboration are related to intellectual property rights, relevance to the mandates of the public and private partners, transparency, nonexclusivity, and resource sharing, and legal and regulatory frameworks need to be developed.

Business models and the postharvest value chain

Enhancing the delivery of research and enabling wide-scale adoption of postharvest technologies requires a holistic systems perspective as well as actor-oriented interventions. This, in turn, requires new strategies that integrate cross-sector resources and capabilities, including direct engagement of the private sector. Although much has been written on the concept of the value chain, first described by Michael Porter in his landmark book (1985), only in recent years has the concept been extended and embraced by NGOs and public-sector organizations as a means of addressing economic and livelihood needs of the poor. This offers new opportunities to disseminate agricultural research and technologies using a wider array of partners and channels as an alternative to more traditional "top-down" approaches to delivery and extension. As postharvest losses remain quite high and postharvest operations involve numerous points, processes, and actors in the postharvest chain, a value chain approach can help identify both technical and nontechnical constraints and better target interventions that focus on practices and behaviors of agents acting in an entire "value" system.

Several projects are starting to implement value chain approaches for rice. In Lao PDR, ProRice of the Swiss-funded NGO Helvetas has been supporting farmers, rice millers, and exporters since 2006 to establish a certified organic value chain for fragrant rice from Lao PDR (Profil 2008). This includes interventions in the postharvest sector on-farm and at millers to improve quality and ensure traceability, and linking to European markets. In Cambodia, several donors and government organizations are supporting similar efforts for organic brown rice and white rice for local and potential export markets. In Thailand, the government is in the process of establishing a certified good agricultural practice (GAP) rice production chain and the first farmers are already certified. The challenge remains to sustainably implement GAP, including certification, development of new rice brands, and labeling throughout the whole value chain up to export, and to develop and ensure markets abroad where consumers are willing to pay a premium, for example, for certified GAP rice that is produced using guidelines for maximizing resource efficiency. Donors to agricultural research need to commit to projects that include multistakeholder processes and decision making. These naturally need a longer time frame with sustained funding than projects that focus on component technology improvements alone.

Alongside value chain approaches, business models are another tool that can help address the sustainable adoption of postharvest technologies. As business models operate at all points of a value chain, they can be used to capture value and benefits of adoption as well as provide farmers and other chain actors with new income-earning opportunities. More recently, the innovative concept of an "open" or "borderless" business model has been introduced to help overcome technical and nontechnical constraints to the adoption of PH technologies. The open business model concept is rooted in the open innovation movement that promotes the development and sharing of technology in an "open" systems environment (Chesbrough 2006). While developments in IT fields have been early drivers in this movement (e.g., open-source software), this concept has been shown to readily apply to other technologies and industries, including adaptive learning approaches and participatory development of agricultural machinery (Douthwaite 2002). More recently, the open business model concept has been extended beyond the development of technology per se to address nontechnical constraints to adoption and as an actor-enabling tool. As such, open business models enable enterprises to collaborate systematically with outside partners in the private, public, and NGO sectors to access additional resources, capabilities, and expertise.

In the Philippines, the multistakeholder Learning Alliance established by the IRRI-ADB Postharvest Project has recently piloted hermetic storage technologies among seed growers and suppliers in Bohol, Camarines Sur, and Agusan provinces with links to public, local NGO, and private-sector resources. In Cambodia, business models for contract combine-harvesting services are being adopted with cross-sector support for operator training and farmer awareness of technology benefits. In Vietnam, actor-specific business models for the adoption of PH technologies, such as flat-bed dryers, and marketing support for higher-quality rice are being fostered through the World Bank, ADB, as well as NGO-funded initiatives. Further research and donor support for the application of innovative business model concepts are required for optimal impact and benefit to smallholder farmers.

Future R&D needs

Fifty years of rice research have led to dramatic changes that have enabled rice farmers to keep production on a pace with global demand. The postproduction sector has seen similar successes, especially with stand-alone technologies that did not need much integration into the postharvest chain such as the AFT. But, postharvest losses remained high. Considering the factors causing change outlined in the second section, future postharvest R&D needs to examine the following issues:

1. The increased intensity and yield gains in production call for continued mechanization of harvesting and drying to guarantee timely and high-quality operations with minimum loss. The private sector is developing and providing harvesting machinery for the more common intensive systems with modern dwarf varieties. However, development challenges remain in the areas of machine mobility, performance in difficult crop conditions (lodged crop, long straw), and improving quality, for example, for basmati harvesting. Public-private collaboration can help in speeding up the transfer of suitable harvesting technologies and in providing operators and manufacturers with training. Most operators never received formal

training and therefore losses and harvesting cost are higher than needed.

2. The impact of mechanical drying is so far limited to the Mekong Delta of Vietnam. Improving drying therefore remains the major challenge in postharvest. R&D efforts need to focus further on adapting affordable drying technologies to local needs, supporting the private sector in local production and optimization, establishing quality incentives, linking farmers better to markets, providing financing and extension services, and developing business models for dryer usage.
3. The mode of rice production either for subsistence or for markets where quality matters affects priority setting for R&D and requires better targeting of interventions as suggested earlier in this chapter. Farmers with subsistence rice production need measures to reduce losses at no or minimum cost, for example, through safer on-farm storage. Those producing higher quantities and selling to local low-quality markets benefit from the mechanization of postharvest operations, which results in a reduction in physical losses. Farmers targeting quality markets, either locally or for export, also need technology and extension services in best-practice postharvest management to ensure the highest possible quality. All farmers can benefit from value-adding opportunities and increased access to markets.
4. Market demands affect all players in the value chain even though markets for higher-quality or specialty rice will be limited to specific niches. The development of new rice brands combined with certification, for example, as eco-labeled rice, can open up new niche market channels. However, these offer options for only a few producers targeting such niche markets. Hence, improving quality through better postharvest management will remain a priority for all markets. This is also a key priority for countries such as Cambodia and Myanmar, which are developing into major rice exporters. Mechanization of harvest and postharvest operations in general will also lead to the improvement of paddy quality and thus to higher milling recovery. R&D also needs to look at eliminating the two-system rice milling process and shifting gradually toward bulk handling.
5. Ongoing institutional changes with increased involvement of the private sector in R&D and extension mean that improvements in postharvest operations are best developed through a multistakeholder process. New approaches such as public-private partnerships, the facilitation of multistakeholder platforms and participatory decision making, value chain analysis, and the development of business models can help embrace the different stakeholders and thus increase the probability of successful out-scaling and up-scaling of postharvest technologies and management options.

Conclusions

New, exciting technologies are available for drying and storage, new value chain approaches are being developed and piloted, and the development of business models for the technologies complements technical R&D. Researchers are challenged to make the transition from the old practice of tinkering with nuts and bolts to become change agents and facilitators for initiating sustainable processes for participatory piloting and adaptive R&D, providing necessary support services to users and manufacturers or distributors of postharvest equipment, and generating a favorable policy environment. Given all these developments, there is a good chance to reduce postharvest losses to acceptable levels and improve livelihoods of farmers through value-adding options and to ensure that sufficient rice reaches consumers to feed the ever-increasing world population.

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THEME 3:

The evolving rice market structure

The international rice trade: structure, conduct, and performance

Paul A. Dorosh and Eric Wailes

Introduction

International rice trade has expanded rapidly over the last five decades, increasing almost fourfold between the 1960s and the early 2000s. This increase in trade outpaced growth in world rice production, and thus trade as a share of total production rose from 4.4% to 6.9% over this period. Moreover, this increase in trade occurred in spite of sharp increases in production in most major rice-consuming countries, as rice consumption has also expanded due to rising population and incomes.

Nonetheless, the structure of the world rice market together with regular major government interventions in rice trade make the rice market inherently more unstable than world markets for maize and wheat. There is substantial concentration among rice exporters—the five largest exporters accounting for four-fifths of the trade—and, as a result, production or policy shocks in one or more of these countries have major effects on world prices and trade volumes. Moreover, the role of national governments in the conduct of world rice trade is generally greater than for wheat and maize trade, as many rice-importing countries provide their domestic producers with high protection, and state traders play major roles in several key exporting and importing nations. Instability is also increased by the segmentation of the world rice market into submarkets, including medium-/short-grain rice imported mainly by Japan and Korea, high-value aromatic rice (such as basmati and jasmine), nonaromatic long-grain rice, and broken rice.

In spite of these structural characteristics of the world rice market, however, the experience of the mid-1970s to 2006 seemingly suggested that the problem of large price fluctuations had been solved (Dawe 2002). The large rice price increases in 2007 and 2008 shattered this illusion, though, and called into question the reliability of the international rice market as a source of supply for importing countries. Even before the recent world price surges, few countries allowed domestic prices to be driven directly off world prices (i.e., these domestic markets were not consistently integrated with international markets). After these price surges, few countries are willing to rely as heavily on international rice trade.

This chapter explores the structure, conduct, and performance of the world rice trade summarized above and highlights key factors and policies influencing future developments. Section two describes the composition and volume of the rice export and import trade over time, highlighting the emergence of Vietnam, India, and Pakistan as leading exporters. Section three discusses the structure of rice markets in terms of quality differences for various types of rice and trade barriers that greatly influence trade flows. In section four, we discuss the evolution, conduct, and performance of international prices of rice over time, the price surges in 1973-74 and 2007-08, and recent proposals to stabilize international rice prices. Section five reviews recent quantitative studies that have examined the potential effects of liberalization of the international rice trade policy reforms. Section six concludes with a forward look at key factors that are likely to drive future developments and performance in international rice markets.

The structure of international rice markets

Although the volume of the international rice trade increased almost fourfold from 7.5 million tons in the 1960s to an average of 28.5 million tons from 2000 to 2009 (Table 1, Fig. 1), rice trade was still only 6.9% of total production (up from 4.4% in the 1960s).[1,2] By contrast, international trade in the 2000s of maize (81.3 million tons, 11.8% of production) and wheat (114.2 million tons, 18.8% of production) is

Table 1. World production and trade in rice, wheat, and maize, 1960 to 2009.

Item	Decade				
	1960s	1970s	1980s	1990s	2000s
Production (million tons)					
Rice	174.0	234.0	308.3	371.9	413.9
Maize	230.7	338.7	436.4	544.3	691.7
Wheat	267.5	371.1	489.2	568.1	607.8
Exports (million tons)					
Rice	7.5	9.2	11.9	19.3	28.5
Maize	23.6	50.6	64.5	64.9	81.3
Wheat	52.9	66.5	98.9	105.1	113.9
Exports/production (%)					
Rice	4.3	3.9	3.9	5.2	6.9
Maize	10.2	14.9	14.8	11.9	11.8
Wheat	19.8	17.9	20.2	18.5	18.7

Source: Calculated from USDA data.

[1]Figures on the volume of rice trade from USDA presented in this chapter are based on market years, which vary by country. Market years covering parts of two calendar years are designated using the first year (e.g., 2008-09 is shown as 2008).

[2]USDA data consistently report total rice exports in excess of total rice imports. From 1960 to 2009, annual rice exports were on average 7.7% greater than annual rice imports. Only for 1973-74, 1974-75, and 1975-76 do the data show imports greater than exports (by an annual average of 5.1%). The figures given in the text for total world trade are total exports.

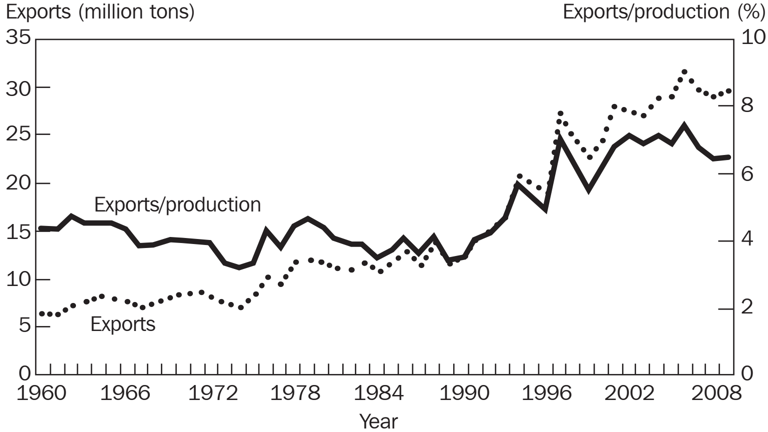

Fig. 1. Rice exports (million tons) and share of production (%), 1960 to 2009. Source: USDA data.

much larger, tending to make these markets more stable. With 90% of the world's rice produced in Asia, most rice tends to be eaten where it is produced and does not enter international markets. Maize and wheat, on the other hand, are produced worldwide but international trade is proportionately larger as demand has expanded, especially in Asian countries, due to changes in diets and increased feed use.

The international rice trade is also characterized by a relatively small number of exporting countries interacting with a large number of importing countries. Moreover, the concentration of exports has increased over time. In the 1960s, the top five exporters had 69% of the world market; in the first decade of the 2000s, this share rose to 81% (Table 2).[3] Since the 1980s, Thailand has consistently been the world's largest exporter of rice, with its volume of rice increasing sixfold from 1.4 million tons per year in the 1960s to 8.4 million tons per year in the early 2000s, and its market share increasing from 19.0% to 29.5% over the same period (Fig. 2). Vietnam, the second-largest rice-exporting country (4.4 million tons per year, 15.5% market share in the early 2000s), became a major exporter only in the 1990s, following marketing and trade reforms (Minot and Goletti 2000). Likewise, India, the third-largest rice exporter (4.2 million tons per year, 14.6% market share in the early 2000s), emerged as a major exporter only after a major economic liberalization in the early 1990s.[4] Although the United States more than doubled its rice production, its share in world trade fell by nearly half, from 19.4% to 11.4%. Myanmar (Burma), the third-largest exporter in the 1960s, also more than doubled its production, but its export volumes fell by two-thirds.

[3]See Siamwalla and Haykin (1983), Barker et al (1985), Roche (1992), and Slayton (2009) for more detailed descriptions of the international trade.

[4]Prior to the economic liberalization, which led to substantial exports of ordinary coarse rice and broken rice, India exported an average of 400,000 tons per year of (almost exclusively) basmati rice in the 1980s (Dorosh 2001, 2008).

Table 2. Rice exports by country, 1960 to 2009.

Country	Decade				
	1960s	1970s	1980s	1990s	2000s
Exports (million tons)					
Thailand	1.42	1.83	4.23	5.46	8.42
Vietnam	0.07	0.01	0.37	2.72	4.41
India	0.01	0.11	0.40	2.15	4.16
U.S.	1.45	2.05	2.43	2.65	3.25
Pakistan	0.14	0.70	1.02	1.59	2.76
China	1.01	1.46	0.70	1.52	1.41
Myanmar	1.10	0.51	0.55	0.24	0.38
Others	4.39	4.52	3.45	4.71	5.54
Total	7.47	9.21	11.90	19.27	28.53
Exports/production (%)					
Thailand	19.3	18.7	33.1	38.3	45.5
Vietnam	1.2	0.1	3.5	15.8	19.3
India	0.0	0.2	0.7	2.7	4.6
U.S.	62.4	63.1	55.8	49.3	51.1
Pakistan	9.3	26.5	31.1	40.0	52.5
China	1.9	1.7	0.6	1.2	1.2
Myanmar	21.7	8.4	7.0	2.4	3.1
Others	7.4	6.2	3.7	4.2	4.1
Total	4.4	4.0	3.9	5.2	6.9
Exports share (%)					
Thailand	19.0	19.8	35.6	28.3	29.5
Vietnam	1.0	0.1	3.1	14.1	15.5
India	0.1	1.2	3.3	11.1	14.6
U.S.	19.4	22.3	20.4	13.7	11.4
Pakistan	1.8	7.6	8.6	8.2	9.7
China	13.6	15.8	5.9	7.9	4.9
Myanmar	14.8	5.5	4.6	1.2	1.3
Others	58.7	49.1	29.0	24.4	19.4
Total	100.0	100.0	100.0	100.0	100.0

Source: Calculated from USDA data.

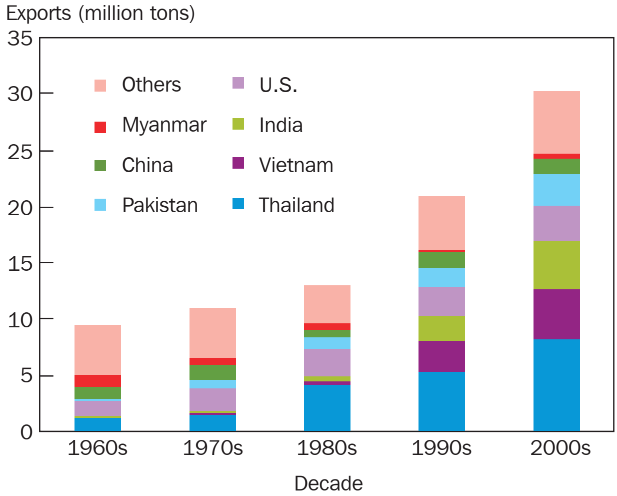

Fig. 2. Rice exports (million tons) by country, 1960 to 2009. Source: USDA data.

The high concentration of exports in only a few countries does not necessarily indicate a lack of competitiveness in markets, since there are many exporting firms. Nonetheless, it does raise the possibility of disruptions and reductions in supply by major exporting countries (including reduced exports as the result of deliberate government policy[5]), leading to higher world prices that adversely affect net consumers in importing countries, but improve the welfare of rice net sellers. Conversely, exceptional production or subsidies on production in exporting countries could depress world prices to the benefit of rice consumers but adversely affect rice producers in importing countries (Dawe 2008, p 115-116). Perhaps most important, though, the high concentration of exports increases the probability that a production shock or a change in trade policy in one or more of these countries could have a major impact on world market flows and prices such as in 2007-08, as described below.

In contrast to rice exports, imports of rice are widely dispersed across countries (Table 3). Imports by the five leading countries in the first decade of the 2000s (Philippines, Nigeria, Iran, Indonesia, and the European Union) were only 27% of the world total; the share of the top 10 countries was only 44%. However, because of market segmentation, some of the larger rice importers have had major impacts on world rice prices. Large purchases by state trade in the Philippines in 2007 and 2009 are examples in which an individual importer contributed greatly to world price destabilization. Indonesia's rice imports accounted for 10% and 15% of world trade

[5]Export restrictions by India and Vietnam were in fact a major factor in exacerbating world rice price increases in 2007 and 2008 (Dawe and Slayton 2010). A rice exporters' cartel could have similar effects on a medium-term basis, though such a cartel would be difficult to maintain (Dawe 2008).

Table 3. Rice imports by country, 1960-2009.

Country	Imports (million tons)					Imports/availability[a] (%)				
	1960s	1970s	1980s	1990s	2000s	1960s	1970s	1980s	1990s	2000s
Philippines	0.16	0.15	0.17	0.62	1.65	6.0	3.9	3.2	9.0	15.5
Nigeria	0.00	0.20	0.53	0.59	1.63	0.5	38.2	39.3	24.6	38.5
Iran	0.01	0.31	0.72	1.16	1.27	2.5	29.3	42.6	45.1	44.1
Indonesia	0.72	1.37	0.31	1.79	1.24	7.4	9.2	1.3	5.7	3.6
EU-27[b]	0.62	0.71	0.72	0.70	1.22	58.1	59.7	52.2	38.4	45.7
Saudi Arabia	0.13	0.24	0.50	0.76	1.20	98.7	99.3	99.6	100.0	100.0
Iraq	0.03	0.21	0.41	0.53	0.95	19.9	66.3	81.0	77.8	88.6
Bangladesh	0.32	0.32	0.31	0.70	0.84	3.4	2.9	2.2	4.0	3.3
Côte d’Ivoire	0.05	0.12	0.27	0.37	0.80	25.8	31.9	45.8	45.3	62.8
Senegal	0.15	0.21	0.33	0.49	0.77	70.4	77.4	80.7	81.7	84.6
South Africa	0.07	0.09	0.21	0.48	0.76	100.0	100.0	100.0	100.0	100.0
Malaysia	0.38	0.25	0.33	0.50	0.74	34.5	18.2	23.7	29.6	35.7
Brazil	0.00	0.11	0.31	0.81	0.70	0.0	2.4	5.2	11.6	8.9
Japan	0.36	0.03	0.04	0.54	0.67	3.5	0.3	0.5	6.7	9.2
Cuba	0.20	0.20	0.15	0.33	0.57	68.8	45.5	32.2	55.0	63.9
Mexico	0.01	0.03	0.06	0.30	0.57	2.5	8.9	15.5	58.2	76.7
U.S.	0.01	0.01	0.08	0.26	0.56	1.2	1.2	5.2	10.6	18.5
China	0.00	0.04	0.31	0.52	0.47	0.0	0.0	0.3	0.5	0.4
Others	3.69	4.34	4.93	6.58	9.83	5.4	4.9	4.3	4.5	5.5
Total	6.89	8.94	10.69	18.02	26.43	4.4	4.1	3.8	5.1	6.6

[a]Availability is estimated as production less 10% for losses, plus gross imports. No adjustment is made for changes in stocks.
[b]Data for the 1960s through the 1990s (1960-98) are for the EU-15.
Source: USDA data.

in the 1960s and 1970s, respectively (and 7.4% and 9.2% of national net availability). During these years, Indonesia's imports had major impacts on world rice markets.

Key actors in the international rice economy include private traders and millers; state trading agencies and government ministries; and producer, milling, and trade associations. The level of price competitiveness among the differentiated rice flows varies considerably based upon established trading relationships, potential export suppliers, and information costs associated with price discovery, technical and tariff trade barriers, and other aspects of trade policy.

International rice market segmentation: rice type and quality

In addition to geographic concentration of exports and the thinness of markets discussed above, another important structural characteristic of the global rice market is substantial market segmentation by rice type and quality. Rice trade occurs for rough rice, brown rice (husked or cargo), milled rice, and brokens. In addition, trade flows of parboiled rice (both brown and milled) and fragrant rice add additional complexity. Finally, rice trade is also differentiated by grain length (long, medium, and short), cooking quality (stickiness), and milling quality (percent brokens). This complex level of market segmentation makes price discovery costly and amplifies price movements as substitution in demand for rice type and quality tends to be inelastic with respect to prices (Wailes 2002).

Low degrees of substitutability for rice exist both on the demand (mill and end-use) and supply sides. On the demand side, the closest substitute is wheat, particularly important in South Asia (Pakistan and India). In many Asian nations, per capita consumption of rice is declining and as a staple food it has become an inferior good with respect to income. It is being substituted out of household diets by higher protein foodstuffs such as meats, as well as by increases in the consumption of fruits and vegetables. With respect to supply, different rice varieties require different climatic conditions and production and milling technologies. This limits the ability of producers and millers to respond to price incentives as a guideline in selecting which type of rice to produce and mill. Rice production generally benefits greatly from access to plentiful supplies of surface water or groundwater and heavier soils that can maintain flood conditions. Although the ability to grow crops other than rice in the wet season is limited in many ecologies, there is much greater flexibility in the dry season, a season that, since the advent of the Green Revolution, has accounted for an ever greater share of rice production.

Long grain (including rough, brown, milled, parboiled, and various degrees of brokens) typically accounts for more than 75% of global rice trade. Medium- and short-grain rice (primarily brown or milled) combined account for about 12% of global trade. Fragrant or aromatic rice accounts for about 12%. Specialty rice—primarily glutinous rice—accounts for most of the remainder.

The conduct of international rice markets: trade barriers

Trade barriers are a significant feature of international rice trade. The major types of distortion in world rice markets are import tariffs and tariff rate quotas in key importing countries and price supports in key exporting countries. In 2000, the global trade-weighted average tariff on all rice was 43.3%. Markets for medium-grain rice are far more distorted than markets for long-grain rice due to tariff rate quotas (TRQs) and quotas in the major medium-grain rice-importing countries of Japan, Republic of Korea, and Taiwan. Global trade-weighted average rice tariffs in 2000 for markets for medium- and short-grain rice were 217% compared with 21% for markets for long-grain rice (Wailes 2004a).

Price supports for rice producers have been important in the major industrialized countries or regions, including the European Union, Japan, and the United States. Both the EU and the U.S. have shifted much of their support mechanisms to decoupled payments and therefore out of the World Trade Organization (WTO) amber box discipline. Yet, it is clear that, without such payments, producers in these regions would be challenged to maintain current production levels. Much of the price support in Japan extends from the tariffs and TRQ levels. Since 1998, Japan's internal market intervention applies only to maintaining rice stocks for food security and isolation of Minimum Access imports from domestic food markets. Therefore, Japan's notification of domestic support as an aggregate measure of support (AMS) is remarkably low, while at the same time the producer subsidy equivalent measure (PSE), which reflects both domestic and border support, remains extremely high.

In addition to trade protection by rice type, an important dimension of world rice trade is protection for the domestic rice milling industry. This form of protection is expressed in tariff escalation and is especially prevalent in Central and South American nations and the European Union. Tariffs on milled rice are higher than for brown or rough rice. Tariffs on milled rice imports into the EU are more than twice the tariff level for brown rice. In Mexico, rough rice imports pay a 10% tariff while brown and milled rice pay a 20% tariff. The effect of tariff escalation is seen in the reduced trade flows of milled high-quality long-grain rice. Most of this trade goes to nations with low tariffs. Most of the trade in brown and rough rice, however, goes to nations that have high tariffs on brown and rough rice, but even higher tariffs on milled rice. The trade-weighted average tariffs by degree of milling for high-quality long-grain rice are estimated to be 4.3% for milled, 31.4% for brown, and 16.9% for rough rice. This compares with simple non-trade-weighted averages for milled rice of 13.7%, brown rice 18.7%, and rough rice 25.4%.

The greatest degree of protection in world rice trade is for medium/short grain. World export prices of medium-/short-grain rice are lower by approximately 100% as a result of protection by Japan, Republic of Korea, and Taiwan (Wailes 2004b). Currently, very few rice-exporting countries produce medium-/short-grain rice. Although potential to expand the production of medium-grain rice in nontraditional areas exists, an adequate price incentive is lacking to induce the research and development of production systems necessary to compete for these markets. The clear beneficiaries of trade liberalization in medium-/short-grain rice in the longer term, with expanded market access, will be those countries, especially China, that have a competitive advantage in production costs and logistics relative to other traditional medium-grain export competitors, such as the United States, Australia, and Egypt.

Trade liberalization may stimulate the production of medium-/short-grain rice in other countries but currently traded varieties are mainly suitable for temperate climates. Thus, South American production, particularly in Argentina and Uruguay, could develop adapted varieties more quickly. Many other developing countries have tropical or subtropical climates; thus, these countries would likely require some time before commercial development of varieties that would be competitive in a liberalized global market for medium-/short-grain rice. Production capacity for medium-grain rice in Australia and the United States and to some degree in China is increasingly constrained by a lack of irrigation water.

Markets for long-grain rice are far less protected than those for medium-grain rice. Trade barriers in major importing nations for low-quality rice such as Indonesia are estimated to reduce world export prices by as much as 30% compared with prices under full liberalization. The major impact of protection in markets for low-quality rice falls on consumers in these low-income importing developing nations and producers in exporting nations for low-quality rice such as Vietnam, India, Pakistan, and Thailand. Protection in markets for high-quality long-grain milled rice is estimated to reduce world export prices by 10% to 20%.

As a result of slower and longer-term market access reforms allowed for developing countries in the WTO, rice policies in those countries have not changed significantly over the past decade. The lack of rice policy reforms in developing countries has resulted in greater price volatility, which has placed a heavy burden directly on poor consumers or on the government to provide food distribution programs for those in poverty. The coefficient of variation of domestic prices in real terms over the past 20 years was 0.43 in India, 0.26 in Indonesia, and 0.37 in China. These measures of price volatility compare with the coefficient of variation of only 0.24 of the Thai export price in real terms.

The performance of international rice markets: price variability

International rice prices have fluctuated dramatically in both nominal and real terms over the five decades from the 1960s through 2009, with a major price spike in 1973-74 and another in 2007-08 (Figs. 3 and 4).[6] Nonetheless, the long-term trend of real prices has been downward. From 1960 through 2009, real rice prices declined by 2.8% per year (as measured using a logarithmic regression). In broad terms, this decline in real prices reflected increases in production, made possible by the widespread adoption of Green Revolution technology, that outpaced increases in demand (determined largely by population growth and rising per capita incomes), particularly among the major

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[6]Here, we use the U.S. Consumer Price Index (CPI) as a deflator.

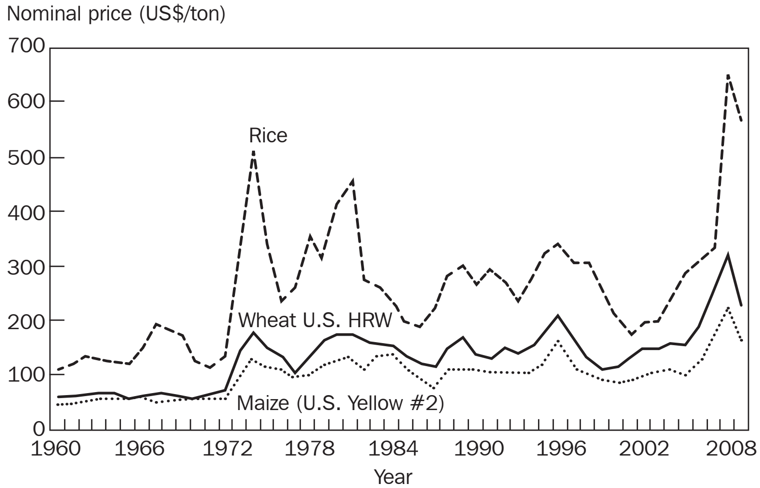

Fig. 3. Nominal prices of cereals (US$/ton), 1960 to 2009. The rice price is indica rice 5% brokens, 1960-2005, spliced with percentage changes in the price of Thai A1 Super (f.o.b. Bangkok) for 2006-09. Data for 2009 are the average of January-June prices. Source: Calculated from IMF and FAO commodity price data.

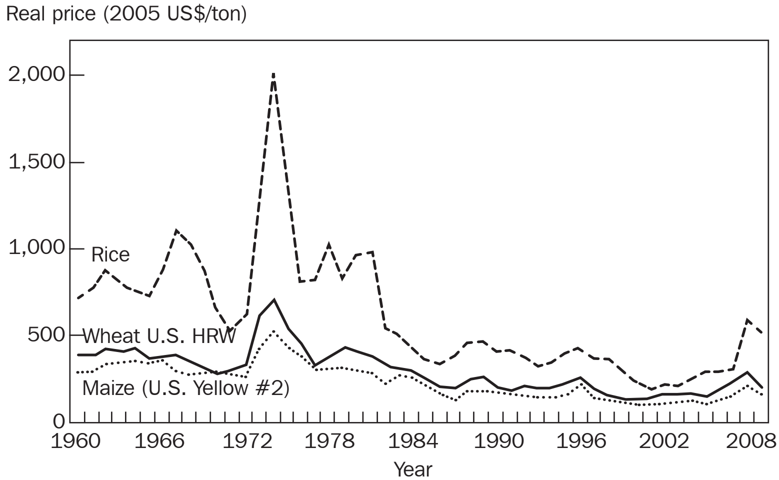

Fig. 4. Real prices of cereals (2005 US$/ton), 1960 to 2009. The rice price is indica rice 5% brokens, 1960-2005, spliced with percentage changes in the price of Thai A1 Super (f.o.b. Bangkok) for 2006-09. Data for 2009 are the average of January-June prices. Real prices are nominal prices divided by the IMF dollar index of commodity prices (index = 1.00 in 1990). Source: Calculated from IMF and FAO commodity price data.

importing and exporting countries in Asia. These declines in real rice prices outpaced the declines in real prices of wheat (2.2% per year) and maize (2.6% per year).

International prices for rice are more unstable than prices of wheat and maize, however, reflecting a thinner market for rice, substantial segmentation across types of rice, and a high concentration of exports by country. From 1960 to 2009, coefficients of variation of annual U.S. dollar prices in real terms were substantially higher for rice (0.58) than for wheat (0.43) or maize (0.45). This pattern holds for all decades except for the 1990s, when relatively large price spikes occurred for wheat and maize (Table 4).

Although international rice prices reached record levels in 2008 in nominal terms, in real terms (i.e., adjusting for overall inflation), the price spike in 1973-74 was much more severe. Real prices for rice in 2008 were less than one-third those in 1974. For wheat and maize, prices in 2008 were below their 1974 levels by 58% and 61%, respectively.

There are also major differences in the causes of the 1973-74 and 2007-08 price shocks, particularly in the greater role of production shocks in 1973-74. In 1972 and

Table 4. Average nominal (US$/ton) and real (2005 US$/ton) cereal prices, 1960-2009.

Cereal	Years						
	1960s	1970s	1980s	1990s	2000s	1980-2006	1960-2009
Rice							
Nominal price	141.2	266.4	280.6	285.1	313.9	268.5	257.4
Coefficient of variation	0.21	0.47	0.32	0.11	0.53	0.25	0.45
Real price	855.3	984.6	543.9	372.8	307.3	401.2	612.8
Coefficient of variation	0.15	0.46	0.44	0.12	0.44	0.47	0.58
Wheat[a]							
Nominal price	62.2	117.9	149.6	148.8	184.2	148.9	132.5
Coefficient of variation	0.05	0.37	0.15	0.19	0.36	0.16	0.42
Real price	381.1	436.9	285.6	194.6	182.4	218.1	296.1
Coefficient of variation	0.09	0.33	0.25	0.18	0.28	0.33	0.43
Maize							
Nominal price	51.8	94.6	113.1	112.9	126.8	110.2	99.9
Coefficient of variation	0.09	0.29	0.18	0.18	0.35	0.17	0.37
Real price	316.9	352.9	216.3	147.7	125.7	162.7	231.9
Coefficient of variation	0.10	0.24	0.26	0.18	0.27	0.36	0.45

[a]Wheat prices are U.S. Hard Red Winter #2 (f.o.b. Gulf of Mexico); rice prices are Thai indica (5% broken) for 1960-2005, spliced with index of Thai A1 Super (f.o.b. Bangkok) for 2006-08; maize prices are U.S. Yellow #2 (Gulf of Mexico). Real prices are nominal prices divided by the U.S. CPI (2005 = 100).

1973, consecutive years of adverse weather contributed to production declines in many parts of the world. In addition, following its own national production decline, the Soviet Union chose to import cereals rather than cut back domestic feed and food consumption, leading to a major surge in international demand on world grain markets (see Timmer 2009b).

Production shocks played a role in the surge in cereal prices in 2007 and 2008, as well, especially poor harvests in several major wheat producers in late 2007,[7] though trade restrictions were more important than in 1973-74 (Table 5). Demand shocks also played a bigger role in the price increases in 2007 and 2008. Increase in demand for maize as bio-fuel contributed to the 54% increase in the international dollar price of maize between August 2006 and February 2007, putting upward pressure on world wheat and rice prices. World cereal market model simulations, however, suggest that the effect of increased bio-fuel demand on maize prices is about three times larger than the effect on wheat prices, with even smaller effects on rice prices (Rosegrant 2008).[8]

Table 5. World price shocks, 1974 and 2008.

Years	Nominal price (US$/ton)			Real price (2005 US$/ton)		
	Wheat	Rice	Maize	Wheat	Rice	Maize
1964-73 average	70.3	158.5	59.4	373.5	846.2	317.1
1974	179.7	517.2	132.0	711.5	2,047.7	522.6
Percent change	156	226	122	91	142	65
1998-2007 average	153.6	252.4	108.0	160.9	262.9	113.3
2008	326.0	650.2	223.1	295.7	589.8	202.4
Percent change	112	158	107	84	124	79
Percent change vs 1974	81	26	69	–58	–71	–61
2009	224.8	568.8	165.7	201.8	510.6	148.8
Percent change vs 2008	–31	–13	–26	–32	–13	–26
Percent change vs 1998-2007	46	125	53	25	94	31

[7]See Headey and Fan (2008) for a more detailed analysis of the causes and consequences of the surge in food prices in 2007 and 2008.

[8]Maize prices began to increase substantially in 2006, more than a year before substantial price increases for wheat. Note also that the rise in petroleum prices substantially predated the rise in rice prices. Petroleum prices rose by 70% between 2004 and 2006, compared with a rice price increase of only 28%. The increase in prices of nitrogenous fertilizer derived from natural gas in many countries may have contributed to higher production costs, lower production, and higher rice prices in some countries, however. See Headey and Fan (2008) for a further discussion of the substantial variation in the timing of price increases of various commodities in 2007 and 2008.

Unlike maize and wheat prices, however, rice prices did not increase substantially until after October 2007, when they rose from $329 per ton to $465 per ton in February 2008. The impact of government policies played a major role in this price destabilization as India placed a ban on its rice exports to boost its domestic supply of cereals following two successive below-average wheat harvests and government wheat procurement outcomes (Dorosh 2009, Timmer 2009b). International rice prices subsequently surged to $907 per ton in April 2008 as Vietnam and Cambodia followed suit with their own export restrictions, leaving only Thailand and the U.S. among the major two exporting countries to supply international markets and increasingly anxious importing countries such as the Philippines (Heady and Fan 2008, Timmer 2009b). Attempts by the Philippines to secure additional rice imports in early 2008, including its willingness to agree to pay Vietnam prices above market prices, only exacerbated the uncertainty and panic in international rice markets (Dawe and Slayton 2010).

With successful wheat and rice harvests in much of the world later in 2008 and a worldwide financial crisis that depressed market demand in the second half of 2008, rice prices gradually fell to $532 per ton by December 2008. Nonetheless, international rice prices in 2009 averaged $569 per ton and were still 94% higher in real terms than their 1998-2007 average (though international real wheat and maize prices were only 25% and 31% higher, respectively, than their 1998-2007 averages).

Proposals to reduce international price volatility

In the wake of the 2007-08 food price spikes, various options have been advanced to stabilize international cereal markets, including regulations on futures market trading and international physical and virtual grain reserves.

Though speculation was likely not a major cause of the surge in food prices in 2008, there is some evidence that it did play at least some role. In late 2007 and early 2008, the share of long positions (obligations to buy) by noncommercial traders in total reportable long positions by commercial and noncommercial traders for maize, wheat, soybeans, and rice increased significantly. Econometric analysis (Granger causality tests of whether past movements in one variable cause current movements in another variable) suggests that this ratio is a statistically significant determinant of current price movements of wheat and rice (Robles et al 2009).[9] Thus, monitoring speculative capital and limiting futures trading (e.g., by setting maximum limits on trading positions and/or increasing the margin deposit requirements) could reduce excessive speculation and thereby help stabilize prices.

International physical grain reserves might also enhance food security and price stability. von Braun et al (2009) have suggested that a modest independent emergency reserve of around 300,000 to 500,000 tons of basic grains (about 5% of current annual food aid flows of 6.7 million tons of wheat equivalents) would enhance emergency response. This grain, supplied by the major grain-producing countries, would be physi-

[9]See also Abbott et al (2008) and Timmer (2008, 2009a).

cally located in or near developing regions, using existing national storage facilities. In addition, a new international coordinated global food reserve could be constituted, composed of national stocks (in addition to pipeline stocks held by private-sector actors for commercial operations). A high-level technical commission would then decide when interventions on spot grain markets were needed.

Another (not mutually exclusive) alternative would be a system of virtual reserves in which member countries would commit to supplying funds, if needed, for intervention in the futures market. In the event of a food price spike, the funds could be used for short sales (i.e., a futures contract to deliver the commodity at a later date at a specified price), thereby putting downward pressure on futures market prices and, as a consequence, spot market prices. Preliminary estimates suggest that such a virtual reserve might require $12–20 billion, equivalent to 30% to 50% of normal grain trade volume (von Braun and Torero 2009).

Implementation of any or all of these options requires overcoming substantial political and organizational hurdles, however. Some large countries may not be willing to cede control over stocks to an international body or group of experts. Nor is it certain that countries that make commitments at a time when supplies are relatively abundant would actually carry through on these commitments in times of scarcity. Nonetheless, some type of improved coordination across countries could help avoid destabilization and costly buildups of excessive national stocks.

Implications of world trade reforms

Trade liberalization in rice is also viewed as an additional means by which to achieve price stabilization and improve food security in the world food markets (McCalla and Nash 2007). Despite being a basic staple food for over one-half of the world's population, international rice trade encounters some of the most protectionist trade policies. Trade measures are pursued to achieve domestic food security and other "multifunctional" public goods in many countries. Among the most important barriers are import tariffs, which for rice are among the highest of all agricultural commodities. Dimaranan et al (2007) report that the estimated average applied tariff rate was highest for rice among all agricultural and food products at 36.4%; processed dairy products had the second highest average applied tariff rate at 19.4%. Disaggregating by rice type, the global trade-weighted average applied tariffs on medium-grain and long-grain rice in 2000 were estimated by Wailes (2004b) to be 217% and 21%, respectively. Other border measures commonly used to distort rice trade, such as import quotas and import bans, are described in greater detail in FAO Trade Policy Briefs and Technical Notes (FAO 2005a, b).

Potential effects of policy reforms on global rice trade: model simulations

Numerous analysts have attempted to assess the impact of policy reforms on rice prices and trade volumes. Most of these studies have examined unilateral and regional reforms, and only a relatively few have examined global rice trade reform or liberalization. These quantitative analyses of policy reforms have differed in methodology in terms of (1) sectoral coverage of the analysis (partial or general equilibrium), (2) time dimension of the analysis (comparative statics covering a single year or multi-year dynamic analysis), and (3) degree of detail on trade flows (net flows or complete specification of bilateral trade flows).[10]

The primary partial equilibrium models include AGLINK (OECD), IMPACT (IFPRI), and the Arkansas Global Rice Model (AGRM-FAPRI). The AGLINK, IMPACT, and FAPRI are all dynamic multicommodity models covering various countries or regions that are linked through trade. In these models, world prices adjust to balance supply and demand in international trade markets. Similarly, the Agricultural Trade Policy Simulation Model (ATPSM) developed by FAO and UNCTAD is a partial equilibrium framework that is multicommodity, multiregion, but comparative static. Designed primarily for simulating agricultural trade policies, the model produces estimates of impacts of policy reform on world prices, trade volumes, production, consumption, and welfare measures.

In terms of modeling outcomes, however, perhaps the most important determinant of the simulation results is whether different qualities and types of rice are modeled or, alternatively, rice is treated as a single nondifferentiated commodity. Only the AGRM-FAPRI and RICEFLOW models disaggregate rice markets into separate long-grain and medium-grain markets. RICEFLOW, developed by the University of Arkansas, is the only spatial, partial equilibrium model that has been used to examine reform in the international rice economy. It produces comparative static results but its novel feature is a high degree of disaggregation by rice types (long-grain, medium-/short-grain, and aromatic), by degree of processing (rough, brown, and milled), and by quality (high and low in terms of percent of brokens).

The computable general equilibrium (CGE) models used to analyze rice trade liberalization include both agricultural and nonagricultural sectors, but their specification of the rice sector is typically simple, without regard to the complex and nonhomogeneous features of the international rice market. The most widely known model of this type is the Global Trade Analysis Policy (GTAP) model used to analyze broad agricultural trade reforms, including rice trade reforms.

Model simulation results of policy reform

Quantitative estimates of policy reform in the international rice market using various modeling approaches are summarized in Table 6. The scenarios analyzed also vary by model but most have included a full policy liberalization scenario where not only free trade liberalization (import tariff and export subsidy removal) but also domestic support subsidies are removed. Other scenarios reflect only free trade liberalization or partial (50%) policy liberalization.[11] Different scenario designs make comparisons difficult because not only are the model parameters different but the base year, projection year, and rice type also vary by study. Despite the variation in approach, however, the

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[10]See FAO (2005b), FAO Trade Policy Technical Notes No. 12, for a more detailed discussion.

Table 6. Quantitative policy reform analysis in the rice sector—selected studies.

Model	Source	Equilibrium type	Base year	Projection year	Scenario	Rice type	Price effect[a] (%)	Trade effect (%)
AGLINK	OECD (2004)	Partial dynamic	2003	2013	50% policy reform	Milled	1.5	
AGRM	FAPRI (2002)	Partial dynamic	2001-02	2011-12	Full policy reform	Milled	10.3	29
					Free trade only	Milled	10.6	27
AGRM	Wailes (2004b)	Partial dynamic	2001-02	2011-12	Full policy reform	Long-grain	22	15
						Medium-grain	80	
					Free trade only	Long-grain	19	16
						Medium-grain	102	
IMPACT	Rosegrant and Meijer (2007)	Partial dynamic	2001	2020	Full policy reform	Milled	13	
					50% policy reform	Milled	6	
ATPSM	Vanzetti and Sharma (2007)	Partial static	2000	n.a.	Full policy reform	Milled	4.5	
					50% policy reform	Milled	2.1	
RICEFLOW	Wailes (2004a)	Partial spatial static	2000	n.a.	Free trade only	Paddy long-grain	X 3.7 M -10	4.4
						Low quality long-grain	X 6.6 M -14	13.2
						Fragrant	X 0.7 M -41	0.7
						All long-grain	X 1.8 M -18	7.0
						All medium-/short-grain	X 91 M -27	58.6
						All rice	X 33 M -14	15.4
GTAP	Dimaranan et al (2007)	General equilibrium dynamic	2001	2007	Full policy reform	Milled	5.5	21.6
					50% policy reform	Milled	2.3	6.9

[a]X refers to the export trade-weighted domestic price and M refers to the import trade-weighted domestic price.
n.a. = not applicable.

general results are as expected: removing policy wedges that lower domestic prices of rice exports relative to border prices (e.g., export taxes) or that raise domestic prices of rice imports relative to border prices (e.g., import tariffs and other import restrictions) result in increases in world reference prices (of exports) and decreases in trade-weighted domestic prices of rice imports.

Assessments of full liberalization have been conducted by AGRM (FAPRI 2002 and Wailes 2004b), IMPACT (Rosegrant and Meijer 2007), ATPSM (Vanzetti and Sharma 2007), and GTAP (Dimaranan et al 2007). When rice trade is modeled as a homogeneous market, the world reference rice price is projected to increase by a range of 4.5% (ATPSM) to 13% (IMPACT). With disaggregation by rice type, AGRM (Wailes 2004b) reported a 22% increase for long-grain rice reference price and an 80% increase for medium-/short-grain rice price, reflecting the higher degree of protectionism in the medium-/short-grain market. The increase in volume of rice trade under full trade liberalization ranges from 15% (AGRM, Wailes 2004b) to 21.6% (GTAP) to as high as 29% (AGRM, FAPRI 2002).

Assessments of a 50% reduction in protection using the AGLINK, IMPACT, ATPSM, and GTAP models provide broadly similar results, about half the magnitude of full liberalization results. World reference rice prices increase by 1.5% (AGLINK) to 6% (IMPACT).

Free trade (tariff and export subsidy elimination) was analyzed by the AGRM (FAPRI) and the world price increases by 10.6%, whereas with the AGRM (Wailes 2004b), which disaggregated by rice type, the long-grain price increases by 19% and the medium-/short-grain price by 102%. The RICEFLOW model framework has even greater disaggregation by rice type, rice quality, and degree of processing. Wailes (2004a) estimated that the trade-weighted export prices for rough rice increased by 3.7%, for low-quality long-grain (more than 10% brokens) rice by 6.6%, for fragrant rice by 0.7%, for all long-grain rice by 1.8%, for medium-/short-grain rice by 90.6%, and for all rice by 32.8%. This study also reported the effects on trade-weighted import prices with declines for rough rice imports of 10%, low-quality long-grain by 14.1%, fragrant by 41.5%, all long-grain by 17.7%, all medium-/short-grain by 27.4%, and all rice by 13.5%.

As noted above, the simulations using these models generally produce consistent results in terms of the predicted direction of price and trade impacts following reform. World reference prices for exports increase, trade-weighted import prices decrease, and rice trade expands. The value of these analyses is their ability to provide quantitative estimates of the impacts of policies on the international rice market, thus giving an indication of the general direction and potential significance of policy reform. The results reflect that, upon disaggregation, effects on prices and trade are drastically different, reflecting the large difference in the nature of the heterogeneous rice market and difference in the degree of protection by rice type, quality, and degree of processing. Finally, perhaps the most important challenge in quantitative modeling of the global rice economy is the need to capture the uncertainty of production and its impact on prices

[11]A more detailed discussion of results for more studies conducted prior to 2005 is given in FAO (2005b).

and trade. Stochastic simulation will be required to begin to understand the potential of policy reform in rice to contribute to greater price stabilization and improved food security.

Conclusions

International rice trade has increased dramatically over the past four decades, but it still represents only a small share (about 7%) of world consumption. Looking forward, it seems likely that rice exports will continue to be dominated by a small group of countries. Thus, world prices are likely to remain inherently unstable, as production shocks occur or trade policy changes in these countries (and in China, which will likely be a major player either as an importer or an exporter). Higher variance in production due to climate change could also add to the instability in prices.

Future growth in trade may be slowed by pessimism regarding the reliability of international markets, however, particularly in the wake of the international price shocks of 2007 and 2008. Adoption of some or all of the proposals to reduce international price fluctuations, such as regulating futures markets trading and establishing (physical and virtual) international stocks, could change this scenario, though. If international markets are perceived to have been made more reliable, countries may be encouraged to increase reliance on trade (or at least to avoid retracting from the world market). WTO reforms could also lead to substantial (up to 14% under the U.S. proposal) increases in trade volumes of medium-grain rice (though only small increases in trade volumes of long-grain rice, an imperfect substitute for medium-grain rice).

Ultimately, poor rice consumers and net rice-deficit farmers in rice-importing countries generally benefit from trade because of lower prices and greater availability. For these hundreds of millions of households, as well as for rice producers in exporting countries, continued expansion of world trade in rice would enhance welfare and promote food security.

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Notes

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Chapter 3.2

Domestic rice price, trade, and marketing policies

David Dawe, Steven Block, Ashok Gulati, Jikun Huang, and Shoichi Ito

Introduction

The price of rice is a key variable for farmers, consumers, and governments in most of Asia, and in many other parts of the world as well. It has obvious economic importance given the widespread poverty in the region, but in many cases it is equally important politically. This chapter will discuss the policies used to influence domestic rice prices, the effects of those interventions on welfare, and how price policies might be improved and made more cost-effective.

As background, the first section of this chapter will assess cross-country and time-series patterns in domestic prices and nominal rates of protection by using various data sets from the International Rice Research Institute (IRRI), Food and Agriculture Organization (FAO), and the World Bank. In analyzing these data, a distinction will be made between price levels and price stability, the latter being a concern of many governments. Although these two concepts are distinct, a concern with price stability can easily lead to important effects on long-term price levels.

Government interventions into domestic rice price formation have been widespread. Since domestic prices rarely follow world market prices on a year-to-year basis, the second section will explain the policies that have been used in various groups of countries to influence domestic price formation. China and India will each be treated separately, given the large size of these two countries. The rest of rice-producing developing Asia, whose combined population is very large but still less than that of either of the two giants, is covered in a third subsection. Japan and Republic of Korea are covered separately given their high levels of per capita income and the policy dilemmas that their rapid economic growth caused for rice price policy. Although the macroeconomic importance of rice is much less in Africa than in Asia, Africa's increasing reliance on imports during the past few decades poses many policy dilemmas that deserve a separate subsection.

The third section of this chapter will examine the impacts of domestic price policy on poverty and welfare for producers and consumers. Given the importance of rice in farm incomes and in consumer budgets, especially for the poor, domestic price policy can have profound effects on producer and consumer welfare. Further, there is tremendous potential for conflict between the two groups given their opposing interests.

In light of the results in the first three sections, the final section of the chapter will examine various options for improving rice price policy so as to contribute to various economic and political objectives.

Setting the stage: patterns in domestic prices

Before discussing the nature and impacts of rice price policies, it is essential to have some basic background information on the behavior of domestic rice prices around the world. Although many authors have shown that the world market price of rice has declined over time (Dawe 2002, Timmer 2010), domestic prices are more relevant for farmers and consumers.

Average levels across countries

We compared average farm-level prices (converted to nominal U.S. dollars per ton of rough rice) in 2003 to 2007 for all 82 countries for which data are available from FAO (2010). The range of prices across countries is substantial—the first quartile of the data is US$184 per ton, while the third quartile is more than double, at $429 per ton. Furthermore, several countries have extraordinarily high domestic prices that are at least 7 times the median price of $239 per ton: Japan, Republic of Korea, Turkmenistan, and Brunei.[1] For comparison, the average world price of rice during this time was $183 per ton of rough rice (converted from milled rice at a ratio of 0.67). This comparison is only crudely indicative, however, as this world price is for a specific quality of rice (5% brokens) at a specific location (Bangkok).

Both GDP per capita and trade status (defined as the share of net imports in domestic consumption for net importers and the share of net exports in production for net exporters, the latter as a negative number)[2] are correlated with the level of prices. Higher levels of GDP per capita and higher proportions of imports in domestic consumption are both associated with higher domestic prices (column 1, Table 1). The coefficient on GDP per capita becomes much smaller in magnitude and statistically insignificant after removing the four high-price countries noted above, however (column 2, Table 1). Regional fixed effects were not statistically significant, and thus were not included in the regressions reported in Table 1.

This pattern is observed in Southeast Asia, for example, where farm prices in the mainland exporters (Thailand, Vietnam, and Cambodia) are below prices in the peninsular and archipelagic countries (Malaysia, Indonesia, and the Philippines), all of which are rice importers.[3] Within South Asia, prices are more similar across countries, with less distinction between exporters and importers. Across the whole sample, the coefficient on the trade status variable in column (2) implies that a change from exports being equal to 10% of domestic production to imports being 10% of domestic consumption is associated with 7.7% higher prices (= (0.10−(−0.10))*0.387).

[1]One shortcoming of this analysis is that the domestic price data refer to a range of different qualities. The broad conclusions are unlikely to change if adjustments were made for this effect, however, as evidenced by country-specific analyses that take into account quality (e.g., Dawe 2008, Cramer et al 1999).

[2]The denominator of the trade status variable is different for net importers and net exporters so that the variable is bounded on the interval [–1, 1].

[3]Although countries can shift rice trade status from year to year, there has been remarkable constancy in the net trade positions of individual countries over the past century (Dawe 2008). Thus, we refer to traditional exporters (Thailand, Vietnam, and Pakistan) and traditional importers (Indonesia, the Philippines, Sri Lanka, and Malaysia).

Table 1. Regression of domestic prices on (2003-2007) GDP per capita and trade status.[a]

Independent variable/statistic	(1)	(2)
GDP per capita	0.107 (0.039)[b]	0.026 (0.543)[b]
Trade status	0.414 (0.012)[b]	0.387 (0.004)[b]
Adjusted R^2	0.083	0.083
Number of observations	81	77

[a]Domestic price is quoted in nominal U.S. dollars per ton of rough rice. GDP per capita is in nominal U.S. dollars per person. Trade status is defined as (Imports – Exports)/(Production + Imports – Exports) for net importers and (Imports – Exports)/Production for net exporters (with Imports, Exports, and Production all in quantity terms). Both of the independent variables are calculated for the period 1998 to 2002. Domestic price and GDP per capita are specified in log form. Only 81 observations are included in column (1) due to a lack of data on GDP per capita for one country.
[b]Values in parentheses are levels of significance (*P* values).

Trends over time

The most striking trend in world rice prices is a declining trend over time, although in the period after 1950 most of the decline was concentrated between 1981 and 1986, as opposed to being a steady decline over a longer period of time (a linear regression of real price versus time has a slightly positive slope between 1950 and 1981; Dawe 1998). But what about trends in domestic prices over the longer term?

We used data from IRRI (2010) and the Distortions to Agricultural Incentives (DAI) data set (Anderson and Valenzuela 2009) to examine this question.[4] All domestic prices were deflated using data on the domestic consumer price index (CPI) from IMF (2009) to compute time series of domestic prices in real local currency terms. We focus this brief discussion on countries for which continuous data exist going back to at least the 1960s and ending in 2004 or later. We ignore several countries that had significant episodes of extremely rapid inflation (e.g., Brazil, Ecuador, Turkey), as the quality of the CPI in such circumstances is suspect.

Simple log-linear regressions of real price versus time were computed for the 15 countries with data meeting the above criteria (Table 2). Of these 15, only four had positive time trends and only two were statistically different from zero—Indonesia and Republic of Korea (*P* values for Pakistan and Sri Lanka were 0.30 and 0.53, respectively). The other 11 had negative time trends, and all were statistically significant at $P<0.01$. Among these 11, the trend generally ranged from −0.4% per year to −2.0% per year (equivalent to cumulative declines over 40 years of 14% to 56%), although the declines in Spain and the U.S. were more strongly negative. These trends compare with world price trends in real U.S. dollars of –3.2% to –4.4% per year (based on data from 1955 to 2007 and 1969 to 2007, respectively; deflation done with the U.S.

[4]FAO (2010) has annual farm rice (paddy) price data for a large number of countries. However, the source advises against comparing data before and after 1991. We have heeded this caution, and thus do not analyze longer-term trends with these data. We also do not analyze IRRI (2010) farm price data that cite FAO as the source.

Table 2. Time trend in real domestic price of rough rice.[a]

Country[b]	Level	Years	Coefficient (%/year)
Australia	Farm	1961-2005	−2.0
Colombia	Farm	1960-2005	−1.7
Dominican Republic	Farm	1955-2005	−1.4
India*	Farm	1961-2007	−1.2
Indonesia*	Retail	1966-2004	+1.3
Japan	Farm	1955-2007	−1.4
Korea	Farm	1966-2004	+2.0
Malaysia	Farm	1960-2004	−0.4
Nepal*	Retail	1969-2006	−1.7
Pakistan*	Retail	1966-2007	+0.1
Philippines*	Retail	1961-2007	−1.0
Spain	Farm	1956-2007	−5.0
Sri Lanka	Retail	1955-2004	+0.1
Thailand*	Wholesale	1961-2007	−1.1
USA	Farm	1955-2007	−3.5

[a]Bangladesh and China do not have time series of both nominal prices and CPI that are as long as the countries listed in Table 2, but they both have large populations that are dependent on rice. Real wholesale prices have declined in both countries since the mid-1980s, reinforcing the general conclusion in the main text.
[b]All data are from Anderson and Valenzuela (2009) with the exception of countries marked with *, which are from IRRI (2010).

CPI). Thus, domestic prices, while they have typically declined, have declined by less than the world price has declined. When data are available for different levels of the marketing system for the same country, the trends are nearly always similar.

Patterns in the nominal rate of assistance (NRA)[5]

The NRA data for rice provide some broad insights into governments' use of trade interventions. First, the NRA estimates conform broadly with the "development paradox," which notes the tendency for poor countries to tax their agricultural sector while wealthy countries subsidize theirs. For the period 1955-2007, the mean level of NRA for rice was –0.025 in Africa, 0.18 in developing Asia, 0.32 in Latin America, and 0.62 in the high-income countries.

Second, the NRA for rice generally correlates negatively with the real world price (Fig. 1). This correlation (over 1955-2007) was –0.77 for Africa, –0.86 for developing Asia, –0.43 for Latin America, and –0.67 for the high-income countries. Figure 2 illustrates the nonparametric relationship between the NRA for rice and the real world

[5] The NRA is essentially the percentage by which domestic rice prices exceed the import parity price (the world rice price plus transportation to the country concerned). Thus, an NRA of 0.18 means that domestic prices exceed import parity prices by 18%. The NRA also includes the value of input subsidies, but these are of minor importance for rice in nearly all countries (see also the next footnote).

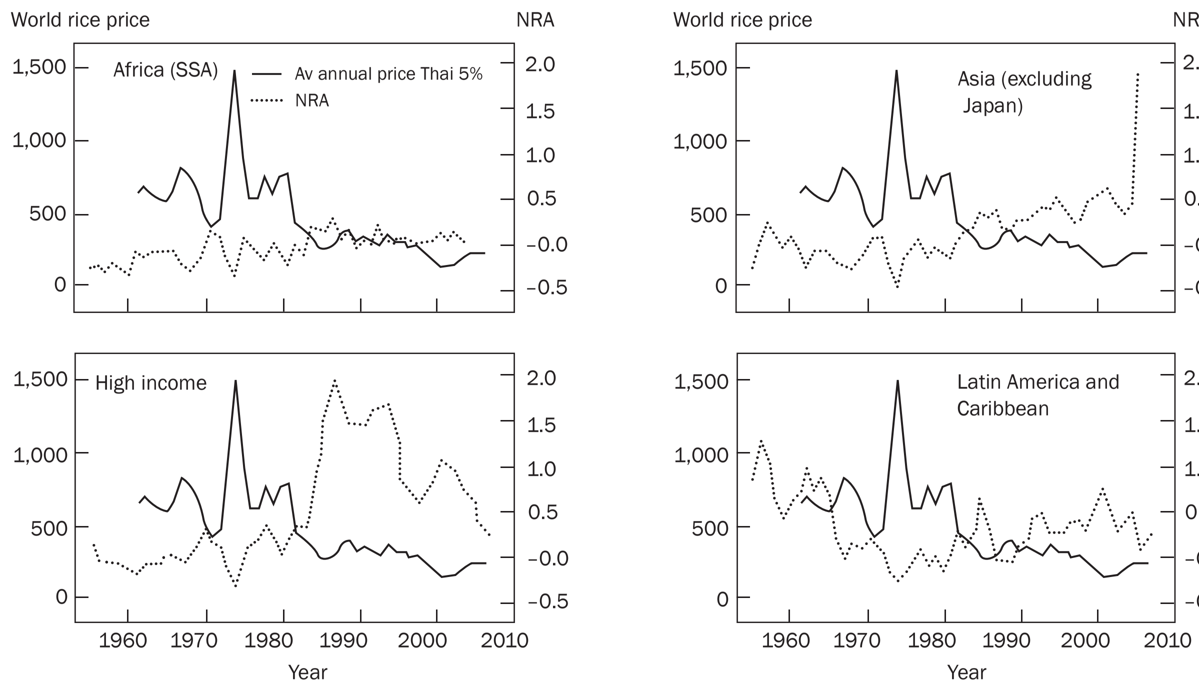

Fig. 1. Nominal rate of assistance (NRA) versus world rice price. World rice price is for 5% brokens, f.o.b. Bangkok, year 2000 US$/ton.

rice price. In general, governments have intervened to raise domestic rice prices above world prices when world prices have been low, and vice versa when world prices have been high. This is broad evidence that governments have tended to use border price interventions in an effort to shield domestic rice markets from international market price volatility (see the next subsection for more evidence). Fig. 2 also distinguishes importers from exporters, illustrating the substantially higher rates of protection of domestic producers among the former.

Other patterns are evident in Figure 1, for example, the substantial increase in the NRA in high-income countries that began in the 1980s. Much of this shift was due to the substantial decrease in the world rice price that began at the same time. We also note the reduced negative correlation between world prices and the NRA in Africa after the mid-1980s, which will be discussed more in the next section on policy instruments.

Decomposing year-to-year variability in the nominal rate of assistance

The nominal rate of assistance to output (NRA_O)[6] as defined in Anderson et al (2008) is affected by at least three key variables: the domestic price, the world price, and the exchange rate used to convert the world price into local currency terms. Changes in the NRA_O can thus be affected by changes in any of those variables. Timmer (1993) found that for a small sample of Asian countries (Japan, Republic of Korea, Malaysia, the Philippines, and Indonesia), changes in the real world price and the real exchange rate were much more important for explaining changes in the nominal protection coefficient[7] than were changes in the real domestic price. From a short-term efficiency perspective, this distinction is not important; what matters is the magnitude of the difference between the border price and the domestic price, not how the difference came about. But from a political economy perspective, it is interesting to understand whether changes in NRA_O are being driven by changes in the real domestic price or by changes in the real border price (which are due to changes in the real world price or the real exchange rate, assuming that real transport costs are unchanged).

In order to investigate whether it was changes in domestic prices or border prices that drove changes in the nominal rate of assistance to output, we ran two regressions for each of the 20 countries for which data were available on domestic prices and the real exchange rate for at least ten years (availability of data on the real world price was not a constraint). The first regressed the logarithm of NRA_O on the logarithm of the real domestic price, while the second regressed the same dependent variable on the logarithm of the product of the real exchange rate and the real world price (this product is the real border price ignoring transport costs). Table 3 shows that, in most cases (15 out of 20), the border price explains more of the variation in

[6]We use NRA_O in this section (as opposed to NRA used in the previous section) to focus on output prices. In any event, NRA and NRA_O are almost identical in the DAI data set for rice: a regression of NRA on NRA_O gives NRA = 0.003 + 0.998 NRA_O, with P values for both coefficients less than 0.000001.

[7]Most of the nominal rate of assistance to output (NRA_O) in the DAI data set is due to border price support as opposed to domestic price support, at least for rice. Thus, NRA_O is similar conceptually to the nominal protection coefficient.

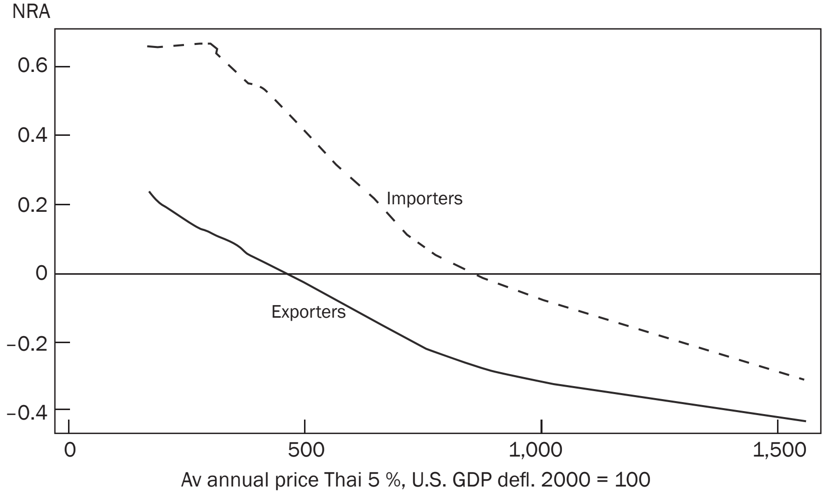

Fig. 2. Nominal rate of assistance (NRA) for rice versus world rice price. Importing and exporting countries, 1955-2007. Data source: World Bank.

the dependent variable than does the domestic price. The average R^2 in the 20 border price regressions was 0.44, while it was just 0.24 in the domestic price regressions. This result suggests that, in most cases, changes in the nominal rate of assistance are being driven more by events external to the domestic rice sector (i.e., either the exchange rate or the world rice price) than by changes in the domestic price itself. The lower correlation between the NRA and domestic prices than between the NRA and the border price suggests that governments have used trade interventions to stabilize domestic rice markets vis-à-vis international rice markets.

Domestic policy instruments

Free trade or price stabilization?

Rice price stabilization has been an objective of many Asian developing countries over the years, and most of these countries have been successful at stabilizing domestic rice prices, a conclusion shared by many authors (Siamwalla and Haykin 1983, Timmer 1993, David and Huang 1996, Timmer 1996, Dawe 2001, Kajisa and Akiyama 2005, Cummings et al 2006). The price stabilization objective goes back in many cases before World War II. The Philippines began to implement price stabilization policies as soon as it achieved Commonwealth status under the USA in 1935, and Indonesia practiced rice price stabilization while still a Dutch colony.

Completely free trade with zero trade taxes has been relatively rare, although Thailand practiced very minimal government intervention for more than a decade starting in 1986. The main benefits of free trade are short-term efficiency gains, more resources for other government expenditures such as public goods, and fewer

Table 3. R^2 of regressions of ln NRA_O on real domestic price ($\ln P_d$) and real border price ($\ln P_b$).

Country	$\ln P_d$	$\ln P_b$
Australia	0.19	0.39
Bangladesh	0.25	0.04
Brazil	0.24	0.05
China	0.14	0.10
Colombia	0.01	0.68
Dominican Republic	0.00	0.21
Indonesia	0.00	0.45
Japan	0.27	0.92
Korea	0.67	0.93
Malaysia	0.00	0.67
Mexico	0.19	0.38
Mozambique	0.00	0.00
Philippines	0.16	0.74
Sri Lanka	0.03	0.17
Thailand	0.47	0.70
Turkey	0.64	0.20
Uganda	0.35	0.83
U.S.	0.51	0.43
Vietnam	0.53	0.70
Zambia	0.05	0.12

opportunities for corruption. The magnitude of the short-term efficiency gains in the presence of market failures has been questioned by Timmer (1989) and Dawe (2001), and indeed Timmer (2002) argues that price stabilization in Indonesia made a substantial net positive contribution to economic growth even after deducting the short-term efficiency losses incurred by not following short-term world price movements. Cummings et al (2006) point out that there have been substantial costs to many of the price stabilization programs, in terms of both corruption and foregone opportunities for investment in public goods.

Because free trade has been so unusual for rice, it is worth describing domestic policies in some detail. And, because policies vary widely from one country to another, it is helpful to have separate subsections for different groups of countries.

China

Because of declines in rice area in recent years, rice now accounts for a slightly smaller percentage of total area harvested in China than does maize. Nevertheless, rice is the most important source of calories in the Chinese diet, and it is the staple food in southern China (maize is used primarily as feed).

Rice policies in China have undergone a fundamental transformation during the past 30–35 years, changing from a crop that was highly regulated and controlled to one for which the market plays a much greater role. The household responsibility system

(HRS) gave farmers, as opposed to communes, control over the output produced by the farm in 1979 although there was still a quota for delivery to the state (changes occurred gradually over a period of several years). The HRS was responsible for the greater part of the large increase in production during the early reform period (Lin 1992). At the same time, the government increased the above-quota prices received by farmers (Sicular 1988), further improving the incentives for production. Nevertheless, this was not a liberalized marketing system—the government still set both the quota price and the above-quota price. The quota system was also responsible for taxing farmers, as the nominal rate of assistance on rice was negative every year between 1981 and 1995, typically at around –35% (Huang et al 2009).

Gradually, however, the marketing system became more liberalized. In 1980, there were only 241,000 private and semi-private trading enterprises registered with the State Markets Bureau; by 1990, there were more than 5.2 million (deBrauw et al 2004). Except for 1984 to 1986, when government quota procurement peaked at 25–30% of production due to the surge in production in the wake of reforms, government quota procurement declined slowly from about 20% in 1978 to 14% in 1997. Then, between 1997 and 2003, government quota procurement of rice declined from about 14% of production to zero. Thus, China now has a largely unfettered domestic marketing system.

Controls still remain in the international trading system, however. China is a net exporter of nonaromatic rice, and the government retains de facto control over the quantity of exports (i.e., private trade is not free to choose the quantity of exports), which allows China to insulate its domestic rice economy from the world market. Thus, during the world rice crisis in 2008, China's domestic prices stayed largely constant while world prices soared (Yang et al 2008, Fang 2010). China does import aromatic rice (primarily jasmine rice from Thailand), and, after China joined the World Trade Organization (WTO) in 2001, rice has been managed under a tariff rate quota (TRQ) system. The quota level increased from 2.66 million tons in 2002 to 5.32 million tons in 2005, and imports within the quota have a tariff of 1%. The out-of-quota tariff rate is 65%, but, so far, this rate has been irrelevant, as China's imports are always well under the quota.

Despite the restrictions on international trade, domestic prices in China have generally been close to world prices of comparable quality in recent years, as the nominal rate of assistance averaged close to zero between 2001 and 2006 (Huang et al 2009).

India

Rice is a basic staple of Indians, and accounts for a larger share of caloric intake than any other food. In addition, rice has the most area harvested of any crop in the country. Given that the country still has about a quarter of its population below the poverty line, the domestic price of rice is critical to the well-being of millions of consumers as well as producers, and is therefore monitored very closely by the government. The importance of rice to both farmers and consumers leads to the classic food policy dilemma, and thus to a multiplicity of policies. On the one hand, the government follows a policy of "remunerative prices" for farmers by assuring them a minimum support price (MSP) for rough rice. On the other hand, it procures rice through rice millers under a levy system, whereby rice mills have to give a certain percentage of common milled rice (basmati rice is exempt from the levy) to the government at a fixed price. This levy ratio differs from state to state, but generally hovers between 50% and 75% of the market price in rice-surplus states (Gulati and Dutta 2010). The reason the government imposes this levy on rice millers is that it wants to procure ample quantities to feed its public distribution system (PDS), which distributes rice (and wheat) to poor people at a much lower price (generally about half) than the market price.

It is worth noting that farmers benefit not only from a minimum support price for rice but also from some important subsidies on fertilizers, power, and irrigation water. These subsidies are not specifically targeted to rice farmers, but, given that rice is the most prevalent crop and that rice production uses large quantities of these inputs, a fair proportion of these subsidies ends up with rice farmers. The value of these input subsidies adds up to as much as roughly 10% of the MSP.

The government also follows quite restrictive marketing and trade policies for rice (and wheat). For example, whenever there is concern over grain shortages, it imposes not only export restrictions, but can also suspend rice from future trading, impose internal movement restrictions, and impose stock limits on private trade (as was done with common rice in October 2007). Government intervention in the rice market in terms of procurement is to the tune of 25% to 30% of total rice production in the country, and almost 40–50% of the marketed surplus, making the government by far the nation's largest rice trader. Given the multiplicity of policies, it is difficult to measure the net impact on farmers. Compared to what prices would have been if the government had followed an open and free trade policy, both domestically and internationally, Gulati and Kelly (1999) and Gulati and Pursell (2009) have found that the net impact of these remunerative and restrictive policies ("one foot on the accelerator and another on the brake") on rice farmers is that of net taxation in most years.

During 2007-08, when international rice prices reached unprecedented levels, Indian rice prices increased much less. Although the MSP for rice increased by 37% during the two-year period from 2006-07 to 2008-09, the issue price of rice for the public distribution system has remained constant for five years (in real terms it has been falling). Market prices were controlled through restrictive marketing and trade policies on the one hand and enlarged food and fertilizer subsidy schemes on the other. These subsidies have become very large (hovering around $30 billion, a little more than 3% of GDP) and contributed to a large fiscal deficit.

Developing Asia[8]

The instruments used to implement price stabilization policies in other developing Asian countries have been a mix of trade policies coupled with domestic procurement

[8]Use of the phrase "Asian developing countries" in this subsection excludes China and India, which were discussed earlier.

and distribution. In terms of trade policy, there have been two basic approaches. One is to have the government set the export tax or import tariff and allow the private sector to determine the trade volume at the resulting price. In order to stabilize prices, the trade tax must vary with both world market conditions and domestic production. For example, if world prices are low, then the export tax should also be low (while import tariffs would need to be high). Thailand operated such a variable export tax system for many years (Siamwalla 1975), and Bangladesh in recent years has used an ad hoc variable rice import tariff in response to domestic and world market conditions (Dorosh 2008). This policy was successful at keeping prices stable during the "flood of the century" in 1998 that caused a drop in rice production—a zero tariff encouraged large inflows of supplies from India by private traders (Dorosh 2001). The same policy was less successful during the recent world food crisis. Sri Lanka also uses a variable tariff that is often temporarily lowered in the lean season just prior to the wet-season harvest, when domestic prices are at seasonal highs (Weerahewa 2004).

The other approach to trade policy is to have the government determine the volume of trade directly. The volume must vary from year to year in order to stabilize the domestic rice economy against fluctuations in domestic production. Among importers, both Indonesia and the Philippines have used this approach to rice trade policy, as has Vietnam, an exporter, which uses temporary quotas to limit exports on occasion in order to stabilize domestic prices. In theory, the private sector could undertake the actual logistics of trade under this type of policy (and this in fact does occur on occasion), but in practice trading tends to be dominated by the government. Greater government involvement has often led to allegations of corruption (Cummings et al 2006), while the scope for corruption is arguably less when the government is involved only in setting the trade tax and then allowing the private sector to determine the volume of trade.

In terms of domestic procurement and distribution, varying degrees of government involvement have occurred. China and India, discussed earlier, have procured a relatively large percentage of the domestic harvest. In the 1970s, Sri Lanka procured about one-third of the total crop on average, with a maximum of about half in some years. Generally speaking, however, the percentage of the harvest that has been procured has been lower in developing Asia outside of China and India, thus allowing for greater development of private marketing systems. Indonesia, for example, procured (through BULOG) on average only 5% of the total crop (1969 to 1996), leaving the private sector responsible for the remainder. The Philippines, Bangladesh, and Sri Lanka in recent years have procured even less. Historically, Thailand has procured only small shares of the crop as well, although that has changed recently.

Procurement and distribution have often been in defense of floor and/or ceiling prices, although in some instances the prices are intended merely as procurement and distribution prices (e.g., the Philippines). Floor and ceiling prices seem preferable to procurement and distribution prices, because procurement at a price far above market prices creates incentives for corruption, as the buyers for the agency are able to ration access to the high prices. In the Philippines, the procurement price has also been frequently adjusted on an ad hoc basis after the planting season had finished, thus reducing the influence of the price on farmers' planting decisions.

Indonesia was very successful at defending a floor price for many years, which was announced in advance of planting for the main crop. The advance announcement and the consistent successful defense provided stability for farmers. Consistent successful defense required a line of credit from the Central Bank in the event that harvests were large. Ceiling prices were initially explicit but later became more implicit, with the government responsible for making sure that prices did not increase too rapidly.

The quantities procured and distributed in Indonesia varied substantially from year to year in response to interannual fluctuations in production (Timmer 1996). In an especially good harvest, domestic procurement would increase and distributions would decrease, with the difference going into storage, with the reverse happening in the event of a bad harvest. The problem of accumulating excessively old stocks after procuring large harvests was reduced by distributing a minimum fixed amount every month (even if the harvest was large) as part of the salary for the military and government employees. This allowed for rotation of stocks to reduce the amount lost to quality deterioration.

In recent years, Thailand has substantially expanded its paddy pledging program[9] in an effort to increase the prices received by farmers (Poapongsakorn 2010). Between 1993-94 and 2000-01, the paddy pledging program procured on average just 4.8% of the crop, but this share increased to 18.7% on average between 2001-02 and 2007-08. It is perhaps not coincidental that the expansion of the program began at the same time that world prices reached their lowest level in 100 years in real terms, thus causing Thai domestic farm prices to sink to their lowest level in at least the previous decade. In other words, the program was implemented in some sense to stabilize prices. The program was costly, however, as it paid farmers above-market prices and tried to hold supplies off the market for an extended period of time. Indeed, Thai government debts from rice procurement increased by a cumulative $1.9 billion between 1999-2000 and 2005-06. The large fiscal costs have caused some political parties to raise questions about its sustainability.

Japan and Republic of Korea (and other OECD countries)

Rice prices in Japan are possibly the highest in the world. In May 2008, average retail prices of ordinary blended rice in ordinary supermarkets in Tokyo were around 3,600 yen (approximately $36) per 10 kg of milled rice. This was approximately three times the peak world price, although the world rice crisis did not substantially affect Japanese domestic prices. In more normal times, the differential between domestic and world prices is even greater.

[9]Thailand's paddy pledging program loans farmers money for their rough rice at harvest based upon prevailing market prices. If the market price subsequently falls, farmers do not need to repay the loan - they can keep the money and the government keeps the rough rice. If the market price subsequently rises, farmers can buy their rough rice back at the original price and sell to the market at the higher price (Poapongsakorn 2010).

The Japanese rice diversion program began in 1971, and all rice producers were obliged to reduce their production (Wailes et al 1991). Before the diversion program, rice planted area was as large as 3.28 million ha in 1968. It then declined to just above 2 million ha in 1990, and then further declined to 1.8 million ha in 2008. These declines in area have been matched by similar declines in rice consumption, which declined from 12 million tons (milled basis) in the mid-1960s to 8.2 million tons in 2008, a decline of about one-third in about a half century. In per capita terms, consumption was above 120 kg in the 1960s, but was just 65 kg in 2008 (Ito 2009). The diversion program was relaxed to a certain extent under a new Food Law implemented in 1995. Now, a new policy that would strengthen the domestic rice sector and reduce costs of production is being explored.

From 1980 to 1994, Japan imported very little rice, except in 1993 because of a disastrous harvest. Since 1995, however, the Japanese government has been importing rice under the WTO agreement. Imports started in 1995 at 4% of 1986-88 base-year consumption, and increased to 7.2% (approximately 767,000 tons, brown-rice basis) in 2000, a volume that has continued up to 2009. Because current consumption is lower than base-year consumption, imports now account for nearly 10% of total domestic consumption. However, very little imported rice is consumed directly by humans. Instead, most is put into stocks and later used in processing industries or as animal feed due to inappropriate means of importing and marketing by the government. As a result, although rice imports are cheaper than domestic rice, rice imports cost the government 22 billion yen (approx. $189 million at 2006 exchange rates) in 2006 according to the Ministry of Agriculture, Forestry and Fisheries (MAFF).

Although humans consume very little imported rice, rice imports appear to have had a significant impact on domestic prices. Wholesale prices for Koshihikari rice (a high-quality rice) in the first half of the 1990s were generally around 25,000 yen for 60 kg of brown rice. Since July 1995, however, the price declined to 17,000 to 18,000 yen per 60 kg, and it has been unusual for prices to rise about 20,000 yen for even a short period (similar trends occurred at the retail level). The Japanese consumer price index has been very stable during this time, with cumulative inflation of only about 1%, so these changes in nominal prices reflect price changes in real terms.

The current rice diversion program is being reconsidered and may in the future be implemented on a voluntary basis instead of near-compulsory set-aside for all rice producers. A long-run scenario by MAFF (2009) found that removal of the diversion scheme would lead to wholesale prices of approximately 10,000 yen per 60 kg of brown rice, equivalent to about $1,500 per metric ton of milled rice. If efficient producers then expanded production at the expense of inefficient producers, wholesale prices might fall even further, and it is conceivable that Japanese rice would then compete better with rice from California and China, provided that Japanese consumers have strong enough preferences for Japanese rice.

In Republic of Korea, the rice situation is becoming similar to that in Japan. Per capita rice consumption declined from 140 kg in the mid-1980s to about 100 kg in 2008. Just as in Japan, production has also declined, from 6 million tons (milled basis) in 1988 to 4.5 million tons in recent years (Ito 2009). Korean consumer rice prices have been stable in nominal terms at around 180,000 won for 80 kg (about $1,760 per ton at 2009 exchange rates) of milled rice since 2000. Since then, the CPI increased by 30%, implying a 30% decline in rice prices in real terms. Under the WTO agreement, the government started importing rice in 1995, although the shares of imported rice in domestic consumption have up to now been smaller than in Japan. Rice imports in Republic of Korea are scheduled to increase to 408,000 tons by 2014, which should account for nearly 10% of total consumption at that time (Han 2005).

The weakening demand for rice and the strong political power of rice producers in Republic of Korea may lead the domestic rice market to overproduction and an eventual decline in rice prices in the future. In both Japan and Republic of Korea, the development of new rice markets will be essential to prevent domestic rice production from further declines.

Rice policies are clearly less important in other OECD countries where rice is not the staple food, but policy interventions have nevertheless been substantial. The European Community has used intervention stocks triggered by intervention prices, variable duties that vary with the level of imports in the preceding period (high tariffs when preceding-period imports were high and vice versa), as well as preferential duties for certain countries and tariff escalation that makes it relatively cheaper to import rough rice than milled rice (EC 2009). Stabilization again figures prominently, although high tariffs provide substantial protection as well. In the United States, government payments to farmers also vary countercyclically with world prices, providing farmers with some income stability (Slayton 2010).

Africa

Production and consumption of rice in Africa are concentrated in West Africa, which accounts for approximately two-thirds of the market, with most of the remaining market concentrated in East Africa. From 1961 to 2005, rice production in Africa grew at an average annual rate of 3.2% (WARDA 2008), with most of the growth resulting from extensification rather than increased yield per hectare. Over that same period, driven by population growth and urbanization, rice consumption grew by 4.5% per year. As a result, Africa's rice self-sufficiency ratio declined from 94% in 1961 (it was 104% in 1969) to 66% in 2006, and the continent finds itself increasingly dependent on world rice markets to meet its consumption needs (WARDA 2008).

Specific country experiences vary widely. Rice imports in West Africa are dominated by Nigeria, followed by Senegal, Côte d'Ivoire, and Ghana. For share of caloric intake, Senegal is by far the most rice-dependent of these countries, with rice accounting for more than 30% of total calories. Yet, Senegal also has the lowest self-sufficiency ratio among these countries, producing only 15–20% of its rice consumption (WARDA 2008); Nigeria, the region's largest consumer, produces approximately 60% of its own rice needs (Lançon and David-Benz 2007).

Since 1990, rice imports have surged in Nigeria, Senegal, and Ghana, though trade policies have been different in each case. Nigeria's approach to rice policy has been highly interventionist (Lançon and David-Benz 2007). In 1995, Nigeria replaced an official ban on rice imports with a 100% tariff. This tariff was cut in half the following year, but has increased to 110% since 2000. In Senegal, rice imports were a state monopoly until 1996 and subject to quota limits and import tariffs on the order of 38% (until 1994, when the rice tariff was reduced to 16% in the aftermath of the devaluation of the CFA franc). Since 2000, Senegal has maintained a 12% import tariff on rice, in accordance with the common external tariff of the West African trade union. Ghana has implemented a 20% *ad valorem* rice import tariff, in addition to a 12.5% value-added tax. Prior to the initiation of its Economic Recovery Program in 1983, Ghana, too, had maintained an official state monopoly on food trade (Lançon and David-Benz 2007).

More generally, rice policy in Africa can be divided into pre- and poststructural adjustment periods. Prior to Africa's wave of structural adjustment programs in the 1980s and 1990s, the general policy orientation was to maintain cheap food for urban consumers, largely at farmers' expense (Bates 2005). Governments intervened heavily in agricultural markets, acting to limit food prices, but also tending to subsidize inputs. Akande et al (2006) assert—at least in the case of Nigeria—that these subsidies were insufficient to compensate farmers for the reduced output prices. State marketing boards were common institutions throughout African food sectors, generally operating to the disadvantage of local producers (Bates 2005). The elimination of many of these marketing boards, and the liberalization of agricultural trade, was a central feature of structural adjustment programs in Africa.

This withdrawal of the state from rice trade is evident in the "Africa" panel of Figure 1. Prior to the early 1980s, the use of border price interventions for rice was generally oriented to counteract international market price fluctuations. Following the onset of structural adjustment programs in the mid-1980s, the general use of trade policy interventions (as indicated by the mean NRA for rice in Figure 1) was reduced and was less oriented toward counteracting international price swings. The correlation for Africa between the NRA for rice and the world price of rice fell from –0.74 for the period prior to 1982 to –0.12 for the period after 1982.

The rice price dilemma: the welfare effects of domestic price policies

Rice is by far the most important commodity for Asia's poor. In many of the poorest countries, it accounts for more than 60% of caloric intake and more than half of protein consumption (Bangladesh, Cambodia, Lao PDR, Myanmar, and Vietnam), and it is usually more than 50% of crop area harvested in those countries (all data are from FAO 2009). For Asia and the Pacific as a whole, it accounted for 23% of total crop area harvested in 2004 (more than any other crop) and more than 30% of total caloric intake among Asian developing countries. These facts suggest that rice price policy will have profound effects throughout society for both farmers and consumers.

In order to understand the importance of higher rice prices for welfare, poverty, and food security, it is first important to distinguish between net rice producers and net rice consumers. A net rice producer is someone for whom total sales of rice to the market exceed total purchases of rice from the market, whereas, for a net rice consumer, the reverse is true. Net rice consumers will generally be hurt by higher rice prices, while net rice producers will benefit. It is also true that whether a given household is a net rice producer or consumer depends on market prices. Higher prices will discourage consumption, encourage more production, and possibly convert some households from net consumers to net producers. Lower prices could do the opposite.

The concepts of net rice producers and consumers are quite distinct from rural and urban. Although nearly all urban dwellers are net rice consumers, not all rural dwellers are net rice producers. In fact, very small farmers and agricultural laborers are often net consumers of rice, as they do not own enough land to produce enough rice for their family. These landless rural households are often the poorest of the poor. Although some of these laborers work on rice farms and are occasionally paid in rice, surveys show that they do not earn enough rice to sell a surplus on the market. Instead, they need to purchase rice on markets and are likely to benefit from lower prices.

The importance of the rural landless varies greatly from country to country. In many large countries, such as India, Indonesia, Bangladesh, and the Philippines, the landless constitute a significant portion of the rural population. In Indonesia, 45% of rural households on Java do not own any land, and another 20% own less than 0.25 ha (BPS 1996). In the Philippines, the landless constitute 13% of the agricultural labor force, and are one of the poorest groups in the countryside, with income 30% lower than that of rice farmers (Dawe et al 2006). They are less common in Thailand (where population density is lower), China, and Vietnam (due to comprehensive land reforms).

Another important group of poor rice consumers is rural dwellers who own land, but use it to grow nonrice crops. They would benefit from cheaper rice prices. In Indonesia, many farmers plant maize, cassava, and soybeans. In the Philippines, maize and coconut are important crops grown by poor smallholders, with maize farmers being particularly poor.

Higher rice prices will substantially hurt poor net rice consumers because rice is typically a larger share of expenditures for the poor (Table 4). In such circumstances, rice price increases can have important effects on effective purchasing power, even if they do not directly affect nominal income per se. As one example, Block et al (2004) found that, when rice prices increased in Indonesia in the late 1990s, mothers in poor families responded by reducing their caloric intake in order to better feed their children, leading to an increase in maternal wasting. Furthermore, purchases of more nutritious foods were reduced in order to afford the more expensive rice. This led to a measurable decline in blood haemoglobin levels in young children (and in their mothers), thus increasing the probability of developmental damage. A negative correlation between rice prices and nutritional status has also been observed in Bangladesh (Torlesse et al 2003).

On the other hand, farmers who are net food producers are likely to benefit from higher prices, which, other things being equal, will tend to increase their incomes. Since many farmers are poor, higher prices could help to alleviate poverty and improve food security. However, it must also be kept in mind that farmers with more surplus

Table 4. Expenditure shares of rice for the bottom and top expenditure quintiles in several countries where rice is the staple food.[a]

<table>
<tr><th rowspan="2">Country (year of survey)</th><th colspan="2">Bottom</th><th colspan="2">Top</th></tr>
<tr><th>Rural</th><th>Urban</th><th>Rural</th><th>Urban</th></tr>
<tr><td>Bangladesh (2000)</td><td>37</td><td>28</td><td>15</td><td>6</td></tr>
<tr><td>Cambodia (2004)</td><td>28</td><td>21</td><td>8</td><td>2</td></tr>
<tr><td>Madagascar (1993)</td><td>15</td><td>27</td><td>9</td><td>11</td></tr>
<tr><td>Myanmar (1989)</td><td colspan="4">30[b]</td></tr>
<tr><td>Nepal (2003)</td><td>27</td><td>21</td><td>11</td><td>3</td></tr>
<tr><td>Panama (2003)</td><td>9</td><td>4</td><td>2</td><td>1</td></tr>
<tr><td>Philippines (2006)</td><td colspan="2">22[c]</td><td colspan="2">3[c]</td></tr>
<tr><td>Vietnam (1998)</td><td>36</td><td>20</td><td>14</td><td>4</td></tr>
</table>

[a]Value of own-consumption included. [b]Overall share. [c]Average share.
Source: FAO Rural Income Generating Activities (RIGA) database unless otherwise noted. Data for Myanmar are from Myanmar CSO (1993) and are not available by quintile. Expenditure shares for the Philippines were kindly provided by Professor Arsenio Balisacan; raw data are from the Family Income and Expenditure Survey (FIES) of the National Statistical Organization (NSO).

production to sell will benefit more from high prices than farmers who have only a small surplus to sell. Further, in many (but not all) contexts, farmers with more land tend to be better off than farmers with only a little land, so poorer farmers will not receive the bulk of the benefits from higher food prices. In the Philippines, the top quintile of rice farmers has per capita income 15 times that of the bottom quintile, and accounts for 44% of the total marketed surplus, compared with just 6% for the bottom quintile. Since high rice prices benefit farmers only when they have a surplus to sell, most of the benefits of higher prices go to farmers who are in the top half of the national income distribution (Dawe et al 2006). In Thailand, Poapongsakorn (2010) shows that the bottom quintile of rice farmers ranked according to income received only about 4.5% of the benefits of the paddy pledging program that seeks to increase farm prices. One reason for this (just as in the Philippines) is that the poorest farmers do not have irrigated land, and thus produce less.

Another potentially important effect of rice prices works through labor markets. Higher rice prices, by stimulating the demand for unskilled labor in rural areas, can result in a long-run increase in rural wages, thereby benefiting wage labor households in addition to self-employed farmers. Ravallion (1990), using a dynamic econometric model of wage determination and data from the 1950s to the 1970s, concludes that the average landless poor household in Bangladesh loses from an increase in the rice price in the short run (due to higher consumption expenditures), but gains slightly in the long run (after 5 years or more). This is because, in the long run, as wages adjust, the increase in household income (dominated by unskilled wage labor) is large enough to exceed the increase in household expenditures on rice. However, this study used relatively old data, when rice farming was a larger sector of the economy and thus had a more profound impact on labor markets. Rashid (2002), using co-integration techniques and updating the data used by Ravallion (1990), found that, since the mid-1970s, rice prices in Bangladesh no longer have a significant effect on agricultural wages. McCulloch (2008) found no evidence that higher real rice prices were correlated with higher real rural wages. On the other hand, some more recent research implies that the labor market channel is worthy of more study. For example, real wages in Bangladesh rose substantially in 2007 and 2008 in the wake of substantial increases in real rice prices (Hossain and Deb 2010). Lasco et al (2008) also found an effect of rice prices on agricultural wages in the Philippines. Polaski (2008) uses a general equilibrium model of the Indian economy and finds that higher rice prices lead to reduced poverty, due to large effects of rice prices on agricultural wages, which are important to the poor. This latter paper is unclear, however, on the magnitude of its estimate of the elasticity of wages with respect to rice prices, or how that estimate was obtained.

The net effect of higher food prices on welfare and poverty at the country level will thus depend upon socioeconomic structures and the national net trade position (as well as labor market outcomes). Positive impacts of higher prices are much more likely in exporting nations, since a greater percentage of households are probably net producers. Thus, Ivanic and Martin (2008) found that higher rice prices reduce poverty in Vietnam and Pakistan. The result for Vietnam agrees with that from Minot and Goletti (1998), although it differs from that in Zezza et al (2008). In Vietnam, the factors that may contribute to a positive outcome of higher prices are a relatively equal distribution of land and the large share of production (about 20%) that is exported. In Pakistan, the share of production that is exported is even higher than in Vietnam (about 40%) because rice is not the staple food, so it is not surprising that higher prices reduce poverty there. Thailand also exports a large share of production (about 40% since 1990), and Deaton (1989a) and Warr (2001) found that high rice prices reduce poverty there as well. On the other hand, similar results do not necessarily hold for all exporters at all times. Using more recent data and a different methodology, Warr (2008) found that higher rice prices increase poverty in Thailand, a surprising result given the large share of rice production that is exported. In this case, it would appear that most of the benefits from higher prices must go to larger farmers with a large marketed surplus who are not poor (see Poapongsakorn 2010).

Among rice importers, the results are more uniformly negative. Warr (2005) found that higher rice prices increase poverty in Indonesia, as did McCulloch (2008), and similar results were found for Bangladesh and Nepal by Zezza et al (2008). Balisacan (2000) also found that the poorest deciles of the income distribution in the Philippines were net rice consumers, and would thus be harmed by higher rice prices. Ivanic and Martin (2008) found that higher rice prices increased poverty in Cambodia.[10] Sahn's (1988) analysis of Sri Lanka also strongly suggests that high prices hurt the

[10]Although Cambodia is now and historically (the first half of the 20th century) has been a rice exporter, it was a rice importer in 2003, the year of Ivanic and Martin's survey data.

poor. He notes that, in the lowest income quartile in rural areas, 91% of households are net buyers of rice. In addition, he estimates that, among producer households in the bottom quartile, an increase in rice prices at both farm-gate and retail levels would reduce food energy intake even after taking into account the positive effect of higher prices on farm income. Outside Asia, Ivanic and Martin (2008) found that higher rice prices increased poverty in Bolivia, Nicaragua, and Madagascar (all three of which are importers). In Madagascar, Barrett and Dorosh (1996) find that "the roughly one-third of rice farmers who fall below the poverty line have substantial net purchases of rice, suggesting important negative effects of increases in rice prices on household welfare." This finding only concerns rice farmers with land, and ignores the rural landless who are even poorer and are also net purchasers of rice. The authors go on to state that "the poorest rice farmers are quite vulnerable to an increase in the price of their principal crop…. Conversely, the largest, wealthiest 10% or so of farmers stand to benefit significantly from rice price increases." Simulation results from Wodon et al (2008) also suggest that higher rice prices have adverse effects on poverty in Western and Central Africa, which is not surprising given that most of these countries are large importers.

Among the studies reported above, Ivanic and Martin (2008) have the only one that attempted to take into account labor market responses. Their simulation results with and without labor market effects were similar.

In addition to the short-term adverse effects of high rice prices on poverty, high rice prices also raise concerns surrounding long-term economic growth in countries where rice is the staple food. Although there is no solid evidence in this regard, high rice prices (in countries that choose to adopt such a policy) might end up reducing their international economic competitiveness by raising the price of the wage good, thus making wage rates less competitive and discouraging investment in labor-intensive employment that promotes long-term economic growth. High rice prices may also impede diversification into labor-intensive higher-value crops.

To summarize, it appears that the effects of higher rice prices on poverty are generally negative in countries where rice is the staple food. Among all the studies listed above, Vietnam is the only exception to that rule (the case of Thailand is less clear). The effects on long-term economic growth may also be negative, although research is needed in this area.

Price policy options for the future

Rice price policy is a controversial subject. Before describing the various aspects of that debate, however, it seems worthwhile to distinguish once again between policies that alter the long-run level of prices and policies that alter only the variability of prices.[11]

[11]It is true that policies that affect the variability of prices can also affect the long-run level of prices, for example, if the world price exhibits a consistent trend in one direction or the other. Nevertheless, the distinction seems useful, provided it is kept in mind that the two are not completely independent.

It is also important to be clear that the world price is the relevant benchmark for judging the levels and stability of domestic prices. Some may argue that the world rice price is irrelevant to domestic policies because of a divergence between social and market prices, or because of distorted policies in wealthy countries. In addition, the world rice market is certainly thinner than those for wheat and maize. Nevertheless, many transactions take place on this market (7% of world production is far from being a trivial share) and the world price is the short-term opportunity cost of obtaining more supplies. Although there are arguably externalities to rice production that will cause the true social price of rice to deviate from the world market price, these externalities are both positive (e.g., groundwater recharge, prevention of soil erosion) and negative (e.g., methane emissions, fertilizer and pesticide use) and it is not at all clear whether the world price understates or overstates the true social price. Furthermore, if environmental externalities exist, policy instruments other than the rice price will be more efficient at achieving environmental goals (Chang et al 2005). Finally, policy distortions in wealthy countries affect primarily the market for japonica rice, which is much less relevant to developing countries than the market for indica rice (FAO 2005, Dawe 2008). Thus, when assessing either the long-run level of prices or the variability of prices, it makes sense to use the world indica market (e.g., Thai 100B f.o.b. Bangkok) as the basis for comparison.

Are price policies justified?

In general, it seems hard to justify sustained departures of average domestic prices from world market prices on either efficiency or equity grounds. In terms of static efficiency, sustained deviations from the world price can lead to large misallocations of scarce resources that increase with the square of the deviation from the world price, meaning that losses increase exponentially as the deviation gets larger. In terms of dynamic efficiency, attempts to consistently enforce a domestic price higher than the world price may lock farmers into rice and out of more dynamic high-value crops, and they may lose the ability to learn and adjust dynamically to changing market conditions, a skill that will be of increasing importance for farmer-entrepreneurs in the future. Consistent price differentials also encourage excessive rent-seeking behavior.

In terms of welfare, it seems to be a reasonably universal conclusion that higher rice prices increase poverty in countries where rice is the staple food, although Vietnam may be an exception. The world rice crisis of 2008 will undoubtedly encourage many governments to strive for self-sufficiency using higher rice prices. But, given the welfare costs to the poor of high prices, investments in agricultural research and infrastructure so as to improve agricultural productivity and markets would seem to be a far superior way to achieve self-sufficiency.

One policy option would be to offset high producer support prices with consumer subsidies targeted to the poor, but this is fraught with at least two major problems. First, it is very difficult administratively to target the poor—many poor people do not receive the subsidies, and many of the subsidies go to the nonpoor. Olken (2006) found that leakage in Indonesia's program (RASKIN) of distributing rice to the poor was large enough that the program represented a net loss in societal welfare, even when giving the poor substantially more weight in the societal welfare function. Second, raising producer prices above market levels and lowering consumer prices below market levels incurs large fiscal costs (especially in poor countries) that crowd out spending on public goods, thus impairing the long-run growth of the economy. Such schemes are also likely to lead to reduced private-sector involvement in marketing, thus leading to further efficiency losses.

The case for stabilizing prices around the long-term trend of world prices seems stronger, although it is still very controversial among economists and there is no widespread agreement on this issue (Newbery and Stiglitz 1981, Timmer 1989, Anderson and Roumasset 1996, Dawe 2001, Myers 2006). Certainly, such policies appear to be the norm not only in Asia but also historically in Europe. In the 19th century United Kingdom, the Corn Laws contained an explicit sliding scale of tariffs in order to stabilize domestic grain prices. Swinnen (2009) shows that, from the middle of the 19th century, governments in a range of European countries consistently intervened to shield domestic producers from world price movements, raising protection when world prices were low and lowering it when world prices were relatively high. Although such shifts in protection were not formal stabilization mechanisms, they nevertheless served to stabilize domestic prices.

The central question surrounding price stabilization is how to absorb the instability in world supply and demand that leads to changing world market prices. Trade-based domestic price stabilization policies, if successful, shield domestic producers and consumers from that instability, but at the cost of affecting world market prices and making them more unstable. Trade-based stabilization policies can lead to corruption as well, especially when the government plays a major role in conducting trade. Holding large stocks can provide a buffer, but the carrying costs of stocks can be very large, even without taking into account the quality deterioration of grain in storage. Safety net programs are a possible solution, but they place large administrative demands on governments, can have problems achieving wide coverage, may need to be redesigned to serve transitory instead of chronic needs (Alderman and Haque 2006), and are also subject to corruption (Olken 2006). And, a policy of *laissez-faire* can lead to reductions in producer and consumer welfare if credit markets are missing and marginal utility is convex so that welfare losses from price movements in one direction are not compensated by welfare gains from price movements in the opposite direction (Deaton 1989b).

The world market price spike of 2008 has led to a number of proposals to either stabilize prices at the global level or implement mechanisms to shield poor countries from the impact of price spikes that do occur (see the discussion in Dorosh and Wailes, this volume). These proposals are controversial, but even if implemented they would still leave individual countries at the mercy of global institutions. Many countries will strongly prefer to maintain their own policies specifically targeted at their own domestic food security.

Politically, it is hard to imagine that a poor country could tolerate the wide swings in income distribution that would result if domestic prices followed world prices on a month-to-month basis. As a result, there is no realistic chance that governments will simply abandon staple food price policies anytime soon. Given this reality, it makes sense to explore ways to make price stabilization more cost-effective (Cummings et al 2006). This is especially important because the benefits of stabilization decline as economies grow and the importance of rice to the economy declines.

Trade versus storage, private sector versus public sector

In order to improve the cost-effectiveness of price stabilization policies, it will be important to use trade as much as possible, as opposed to storage, so as to avoid high carrying costs and quality deterioration of grain in storage (Dorosh 2009). Both infrastructure and foreign exchange availability have improved tremendously in many countries (Rashid et al 2008), making trade increasingly attractive relative to storage. Despite these trends in infrastructure development and foreign exchange reserves, government stockholdings (as a percentage of production) do not seem to be declining to any appreciable extent over the medium term in either the Philippines or India. In Thailand, they have been increasing recently because of the government's price support program.

In addition to using trade as much as possible, it will also be beneficial to use the private sector to carry out that trade. Efficient marketing is an information-intensive activity, and the information is often decentralized across thousands, if not millions, of different locations. Government bureaucracies are not typically adept at reacting quickly to changing information; thus, it is crucial for the private sector to play the dominant role in marketing.

In terms of domestic trade, Indonesia and the Philippines have managed this process quite well by limiting domestic procurement to about 5% of the crop on average, with 95% being handled by the private sector. On the other hand, India has historically been quite interventionist, with a range of restrictions on intranational movement of supplies across both space and time (storage). Thailand has increased its involvement in domestic marketing substantially in recent years.

Looked at over the longer term, private-sector participation in international trade is increasing (Dawe and Slayton 2004). Sri Lanka allowed private rice imports beginning in 1988, with the volume of imports subject to a quota. Beginning in 1995, the quota was replaced with a tariff, which in practice has varied from year to year and seasonally as well. Bangladesh liberalized its international rice trade in 1994, allowing the private sector to import. This liberalization was coupled with complementary measures to expedite customs procedures and avoid re-imposition of anti-hoarding laws. Pakistan fully privatized rice exports in 1996, removing the monopoly formerly enjoyed by the Rice Export Corporation. Vietnam has increasingly allowed private firms to participate in the export trade. Thailand's rice trade has been privatized for some time. It remains to be seen whether the 2008 global rice crisis will reverse some of these policies.

Indonesia and the Philippines have made halting steps toward private-sector participation in international trade. Indonesia did allow private-sector imports for a time, with the private sector accounting for about three-fourths of rice imports between 1999 and 2002. But, since then, import bans and more restrictive licensing procedures have been frequent. The Philippines allows farmer groups to carry out some of the imports, but their quota is small and nearly always underused.

Despite the improvements, more use could be made of the private sector in carrying out international trade, with the government determining only either the quantity of imports or the tariff/tax in the interests of stabilization. Allowing active private-sector participation with only minimal licensing requirements will increase efficiency and reduce corruption.

Private-sector alternatives to price stabilization

Several private-sector alternatives might be able to provide price stabilization in a more cost-effective manner than current government efforts, including futures markets, forward contracts, and weather insurance. Futures markets for rice have a long history—they operated in both Rangoon and Saigon in the early 20th century (Latham 1986). More recently, both Thailand and India have allowed rice futures markets to operate, although the size of these markets is small. Weather insurance is starting to make some headway in the region, in India in particular. Although these alternatives have some promise, important limitations remain.

First, poor consumers will find it difficult to participate in these markets. Participation in futures markets requires an extraordinary amount of knowledge, and the transaction costs involved in writing forward contracts for individual consumers will be high. It is true that weather insurance is not restricted to farmers and could reduce the risk of disruptions to the livelihoods of landless laborers who depend on the income they gather from harvesting crops. Weather insurance cannot be expected to provide price insurance, however, because prices can vary due to variations in world market prices and exchange rates as well as domestic production variability.

Second, small farmers (who are typically the poorest farmers) will also find it difficult to participate in these markets (although their difficulties may be less than those faced by consumers). Individual small farmers face the same hurdles as consumers with respect to participation in futures markets. Participation in futures markets through farmer cooperatives may offer a solution to some, but most farmers are not members of active, well-run cooperatives. Further, a risk of moral hazard remains if individual cooperative members engage in speculation using cooperative funds. Participation in forward contracts is more promising, but there is likely to be a bias against small farmers due to the transaction costs of negotiating contracts. Weather insurance has potentially lower transaction costs, and may be the most promising of all these approaches for small farmers. Nevertheless, there is a trade-off; lowering basis risk raises transaction costs, because more contracts need to be written that are crop- or area-specific (Morduch 2001, Skees et al 1999). The rapid spread of weather insurance may lead to very standardized contracts that do not serve as effective insurance for many small farmers.

None of this is to say that futures markets should be banned or that the private sector should be prevented from implementing such alternatives. Indeed, they should be encouraged to provide the economy with a wider range of marketing and risk management institutions. Nevertheless, these private-sector instruments are unlikely to provide adequate buffering on their own.

What direction for rice price policies? Improving government price stabilization policies

The difficulties faced by consumers and small farmers in participating in these private-sector alternatives, coupled with the political difficulties involved in a laissez-faire solution, suggest that government-operated price stabilization programs will, as a practical matter, still have a role to play in risk reduction for the poorest members of society. But any such government interventions will be much more effective if they can reduce costs and increase transparency.

Continued use of price stabilization policies has the potential to create large persistent gaps between domestic and world prices. For example, Timmer (1993) shows that much of the large gap between domestic Japanese prices and world prices arose because the government tried to keep domestic prices stable in real terms in the face of declining world prices and an appreciating domestic currency. If, over the longer term, world rice prices fall further, this may result in increasing protectionism, especially if rapid economic development continues and the importance of rice to the economy declines, thereby making it easier to use resources from the rest of the economy to support a smaller number of rice farmers. On the other hand, if world rice prices increase in the long term (due, for example, to (i) higher oil prices and biofuel-mediated linkages between energy and grain markets or (ii) production disruptions due to climate change), then protectionism may be less common. This dependence of protectionism on world prices would be consistent with the European story for wheat and other foods as related by Swinnen (2009).

If protection increases, this will lead to larger efficiency losses in the economy, as well as higher poverty rates in countries where many people still spend a large share of their incomes on the staple food. Of course, these burdens are easier to bear when a country and most of its citizens are relatively wealthy and food-secure. But, for poor countries, as noted earlier, high protection for the staple food could have serious consequences in terms of short-term poverty and long-term growth. Thus, the first key area where price stabilization policies could be improved is for domestic prices to follow medium- to long-term trends in world prices, as opposed to staying constant in real terms.

Second, the costs of implementing policies could also be reduced by allowing a greater role for the private sector in international trade (Dawe 2007), subject only to an import tariff or export tax. This would mean less reliance on government procurement, storage, and distribution. In some countries, it will be important to increase private-sector participation in domestic trade as well by reducing direct government involvement and also by removing restrictions on internal movement of grain. In addition to reducing the burden on government expenditures, such reforms will bring efficiency gains in marketing and might also make price spikes less likely.

Third, panic and hoarding would be less likely if government policies were more predictable and less discretionary. One possibility for achieving this would be a variable tariff/export tax schedule that stipulates in advance the tariff/tax as a function of the world price, as opposed to a system in which the tariff/tax can be changed in an ad hoc manner at any time for any reason (Foster and Valdes 2005). Such a system would provide the private sector with more predictability while simultaneously lowering costs, as the administrative costs of implementing such a system would be close to zero. Such systems may be WTO-incompatible for imports, however, as evidenced by the ruling against Chile described in Foster and Valdes (2005).

Had government policies been more predictable and the private sector played a greater role in international rice trade, the world rice market might have avoided the 2008 price spike. For example, India's export restrictions that began in October 2007 were implemented suddenly and were changed frequently, first from an export ban to a minimum export price (MEP), and then to a series of ever higher MEP. Large and well-publicized government purchases by the Philippines at above-market prices also served to shock the market and send prices surging (Dawe and Slayton 2010).

Price volatility seems likely to continue in the medium term as long as linkages exist between grain and energy markets. Price volatility has political and economic costs, and governments will continue to look for ways to reduce these costs. The optimal solution will vary from country to country, and will most likely involve some combination of targeted safety nets, stocks, and trade policy. But there appears to be substantial room for improvement in nearly all countries in designing more transparent policies that rely more on the private sector.

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Notes

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THEME 4:

Technological opportunities and R&D policies

Rice and global climate change

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Introduction

Climate change has many facets, including changes in long-term trends in temperature and rainfall regimes with increasing year-to-year variability and a greater prevalence of extreme events. The effects of these changing conditions on agriculture are already being seen, yet there are still considerable gaps in our knowledge of how agricultural systems will be affected directly or indirectly by the changing climate, and what implications these changes will have for rural livelihoods (IPCC 2007).

Climate change gives an additional burden to the world's agricultural and natural resource systems that must already cope with the growing food demand driven by population growth and higher incomes in developing countries. The challenge is compounded by the uncertainty and pace of climate change and its effects regionally. It is increasingly clear that climate change will affect agricultural productivity. The temperature and precipitation changes that accompany climate change will require farmers to adapt, but precisely where and how much is uncertain. At the same time, as a significant contributor of greenhouse gases and a potential sink for atmospheric carbon, agriculture can help mitigate climate change.

In this chapter, we discuss the issues for rice agriculture in a world where climate change is increasingly a reality. The purpose of this review is to provide a comprehensive overview on (1) the expected impacts on rice production at different scales, (2) possible mitigation and adaptation options available to rice farmers, and (3) the economic implications of climate change and climate change policy. Many of the impacts of climate change on rice production discussed in this review are applicable to other food crops as well, but, in spite of these commonalities, we highlight several "rice-specific" aspects that warrant an in-depth discussion of the impacts of climate change as well as possible adaptation and mitigation options.

Climate change–induced effects on rice production

The observed and projected effects of climate change are summarized in Table 1, which has been distilled from the recent 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007). A gradual increase in temperature, as reflected in fewer cold days atalnd more frequent hot days, is already discernible in most regions and will intensify in the future. In turn, higher temperatures will further increase the intensity and frequency of heat spells. This trend, which is deemed almost certain for future conditions, has serious implications for agricultural production and human survival. Moreover, the increase in temperature will increase sea level due to thermal expansion of sea water and rapid melting of glaciers and ice caps. As a consequence,

Table 1. Principal conclusions of the IPCC 4th Assessment Report.

Impact of climate change and direction of trend	Probability of trend[a]	
	Recent decades	Future
Warmer and fewer cold days and nights over most land areas	Very likely	Virtually certain
Warmer and more frequent hot days and nights over most land areas	Very likely	Virtually certain
Frequency of warm spells/heat waves increases over most land areas	Likely	Very likely
Frequency of heavy precipitation events increases over most land areas	Likely	Very likely
Areas affected by drought increase in many regions	Likely	Likely
Intense tropical cyclone activity increases in some regions	Likely	Likely

[a]Probability classes: Likely > 66% probability of occurrence
Very likely > 90% probability of occurrence
Virtually certain > 99% probability of occurrence.

Source: IPCC (2007).

fragile coastal and highly productive deltaic rice cultivation areas will be more exposed to inundation and salinity intrusion. In the more immediate term, however, changes in extreme events may exert a stronger effect on agricultural production compared with gradual changes in temperature and precipitation. On the other hand, the predictions of extreme climate events under future climate conditions are attached to even higher uncertainties than those for gradual changes.

Recently, the direct and indirect consequences of climate change for rice production and possible adaptation measures have been examined in extensive reviews (Wassmann et al 2009a, b, Lafarge et al 2010). Moreover, Mackill et al (in this volume) give a detailed description of possible opportunities for rice germplasm improvement to reduce losses associated with abotic stresses such as drought, submergence, and salinity. In this section, we focus on temperature effects in view of some very recent findings and provide only a general description of the effects of droughts, floods, salinity, and increased concentrations of CO_2.

Wide-ranging impacts of drought on rice production and thus on food security have already been documented (Pandey et al 2007). Current projections of climate change scenarios include a strong likelihood of a shift in precipitation patterns in many regions exacerbating an almost universal trend toward reduced water availability for the agricultural sector stemming from competition from other sectors (Bates et al 2008).

Current rice production systems can be considered more vulnerable to drought stress than other cropping systems (O'Toole 2004). However, drought occurrence and effects on rice productivity depend more on rainfall distribution than on total seasonal rainfall. Overall, it is now well accepted that the complexity of the drought syndrome can be tackled only with a holistic approach by integrating plant breeding with physiological dissection of resistance traits and molecular genetics together with agronomic practices.

On the other end of the scale of stress symptoms, flooding can result in sustained submergence of the complete rice canopy, which eventually causes the death of the rice plants. Submergence is increasingly becoming a major production constraint, affecting 10–15 million ha of rice fields in South and Southeast Asia and causing enormous yield losses in different rice-growing countries (Bates et al 2008, Mackill et al, this volume).

Salinity problems are aggravated by high temperatures—and thus climate change—because transpirational demand leads to higher accumulation of salt. This interaction of salt and heat stress is especially relevant in the arid/semiarid regions with high transpirational losses of plants. Moreover, salinity problems will become more rampant in coastal and delta regions affected by sea-level rise (see below).

One of the unknowns in the equation of the impacts of climate change on rice production is the interaction of climate effects with higher CO_2 concentrations. CO_2 affects both stomatal conductance and the photosynthesis apparatus, resulting in associated gains in (1) reduced respiration losses and (2) increased carbohydrate formation. Positive CO_2 impacts, however, decrease over the ontogenetic development of rice plants. This "down-regulation" of photosynthetic rates is an important factor for assessing net impacts and, in the next step, developing improved rice germplasm for higher ambient CO_2 concentrations. Overall, the positive response of rice to elevated CO_2 concentrations can be seen as a crucial mechanism to compensate for or even counteract the detrimental effects of future climatic conditions.

Higher temperatures affect rice yields through two fundamentally different processes, that is, (1) gradual changes in metabolism and phenology and (2) spikelet sterility caused by extreme temperatures (heat waves) beyond certain temperature/humidity thresholds. Rice is grown in many regions where current temperature levels during grain filling are only slightly below the critical limits for spikelet sterility (Wassmann et al 2009a). The dry-season crop is potentially at risk in many regions in Asia, but, as of now, variety selection and flooding of the fields (which reduces heat stress at the canopy level) usually keep the incidence of heat-induced sterility low. Nevertheless, it seems justified to assume that progressive climate change will soon cause heat-induced losses and thus a need for varietal improvement in terms of heat tolerance.

Extremely high temperature during vegetative growth reduces tiller number and plant height, and negatively affects panicle and pollen development, thereby decreasing rice yield potential (Yoshida 1981). High temperature is of particular importance during flowering, which typically occurs mid-morning. Exposure to high temperature (>35 °C) can greatly reduce pollen viability and thus cause irreversible yield loss because of spikelet sterility (Matsui et al 2000). Studies conducted at International Rice Research Institute (IRRI) in the early 1980s demonstrated significant genotypic variation in high-temperature-induced spikelet sterility and tolerant varieties were identified. Tolerance was shown to be associated with specific temporal and spatial characteristics of anthesis, number of pollen grains on the stigma, and tolerance of pollen germination of high temperature. The low degree of stigma exsertion is probably associated with low spikelet sterility under high temperature. Current studies focus on the impact of heat stress on the degree and synchrony of anther dehiscence and stigma receptivity and on postpollination processes. This information can now be used to develop screening tools for the identification of tolerant rice germplasm on a large scale, as well as for the development of a marker-aided breeding system and candidate gene isolation.

One breeding strategy for avoiding high-temperature-induced spikelet sterility is to change the time of day when flowering commences to cooler periods earlier in the day, that is, to escape high temperatures. Wild rice and *Oryza glaberrima* accessions evaluated at IRRI varied by about 3 hours in the time of flowering. The greater heat tolerance of popular cultivar IR64 compared with landrace Moroberekan may be due in part to its earlier and more synchronous flowering during the morning. These lines have been crossed to develop populations suitable for genetic and molecular analysis of the control of floret opening time. Selecting for early-morning floret opening could initially protect rice fertility from future adverse effects of climate change, until more genes and promising physiological pathways of heat tolerance or avoidance become known.

The simulated yield reduction from a 1 ºC rise in mean daily temperature is about 5–7% for major crops, including rice (Brown and Rosenberg 1997, Matthews et al 1997). This yield reduction is mostly associated with a decrease in grain formation, shortening of growth duration, and increase in maintenance respiration. Peng et al (2004) reported that annual average nighttime temperature increased at a rate of 0.04 ºC per year from 1979 to 2003 at IRRI. The increase in nighttime temperature was three times greater than the increase in daytime temperature over the same period. More importantly, rice yield declined by 10% for each 1 ºC increase in growing-season nighttime temperature in the dry season. Ziska and Manalo (1996) suggested that higher nighttime temperatures could also increase the susceptibility of rice to sterility, with a subsequent reduction in seed set and grain yield, but the possible mechanism for this remains unknown.

The effects of increasing nighttime temperature on rice growth and yield are less understood than the effects of extremely high daytime temperatures on spikelet sterility during flowering. Biomass losses from increased maintenance respiration or differential effects of night vs. day temperature on growth and crop phenology have been proposed as possible causes. Information is limited on genotypic variation of rice respiration in response to increased temperature. We particularly lack a clear understanding of the complex interactions between maintenance respiration and developmental stage, plant density/plant spacing, crop water and N status, temperature, and CO_2. Acclimation of maintenance respiration under long-term high-temperature treatment is also poorly understood in rice.

Higher average daily temperature during grain filling has a detrimental effect on at least three components of grain quality: chalkiness, amylose content, and cooking quality (higher gelatinization temperature). High temperature shortens the duration of grain filling because enzymes involved in starch synthesis are sensitive to high temperatures. High nighttime temperature also reduces the milled produce, that is, the yield of whole grains (head rice) after the milling process (Counce et al 2005).

In a recent study, Welch et al (2010) analyzed data from farmer-managed fields to assess the impacts of daily minimum and maximum temperatures on rice yields in six important rice-producing countries of tropical and subtropical Asia. Using a multiple regression model, higher minimum temperature was shown to reduce yield while higher maximum temperature raised it. In turn, Welch et al (2010) project two different stages of yield responses in the future. Increasing minimum temperature will result in an underlying decline in rice yield; this effect will be exacerbated at some point by higher maximum temperatures that exceed the physiological threshold for spikelet fertility. In any case, diurnal patterns of temperature must be considered when investigating the impacts of climate change on irrigated rice in Asia. However, temperature changes are often associated with changes in solar radiation. Zhang et al (2010) used data from 20 experimental stations in China and found that yields were positively correlated with solar radiation. They postulated that the positive effects of higher solar radiation may have counteracted a possible yield decline caused by higher temperatures.

With the sequence of the rice genome now available, and the rapid advancement in cataloguing gene function, it is becoming feasible to relate phenotypic variation to functional allelic variability. In order to secure grain yield and quality in a warming world, it is necessary to embrace new tools and identify genetic strategies to overcome the effects of high temperature on sterility and grain filling and to develop selection tools that will enable rice breeders to continue to select for high yield and high-quality grain in a warmer world.

Regional impact assessments

Sea-level rise in delta regions

South, East, and Southeast Asia contain several mega-deltas, of which nine are larger than 1 million ha (IPCC 2007). Rice production in these mega-deltas forms the backbone of the agricultural sector in many Asian countries and is responsible for a large share of the rice that is internationally marketed (Wassmann et al 2009b). At the same time, topographic settings and vicinity to the coast line render delta regions especially vulnerable to the consequences of climate change, namely, those of (1) sea-level rise and (2) storm surge. Observations from tide gauges indicate that mean global sea level has risen by about 10 to 25 cm over the last 100 years (IPCC 2007). Model projections of future global mean sea-level change, based on projected temperature change, show a rise of up to 1 m (IPCC 2007).

No crop other than rice can be grown under these adverse conditions of unstable water levels and, in many locations, salinity. The elevation map shown in Figure 1 exhibits the large delta areas in Asia and exemplifies their significance for rice production in Vietnam, Myanmar, and Bangladesh. In Vietnam, the Mekong Delta alone

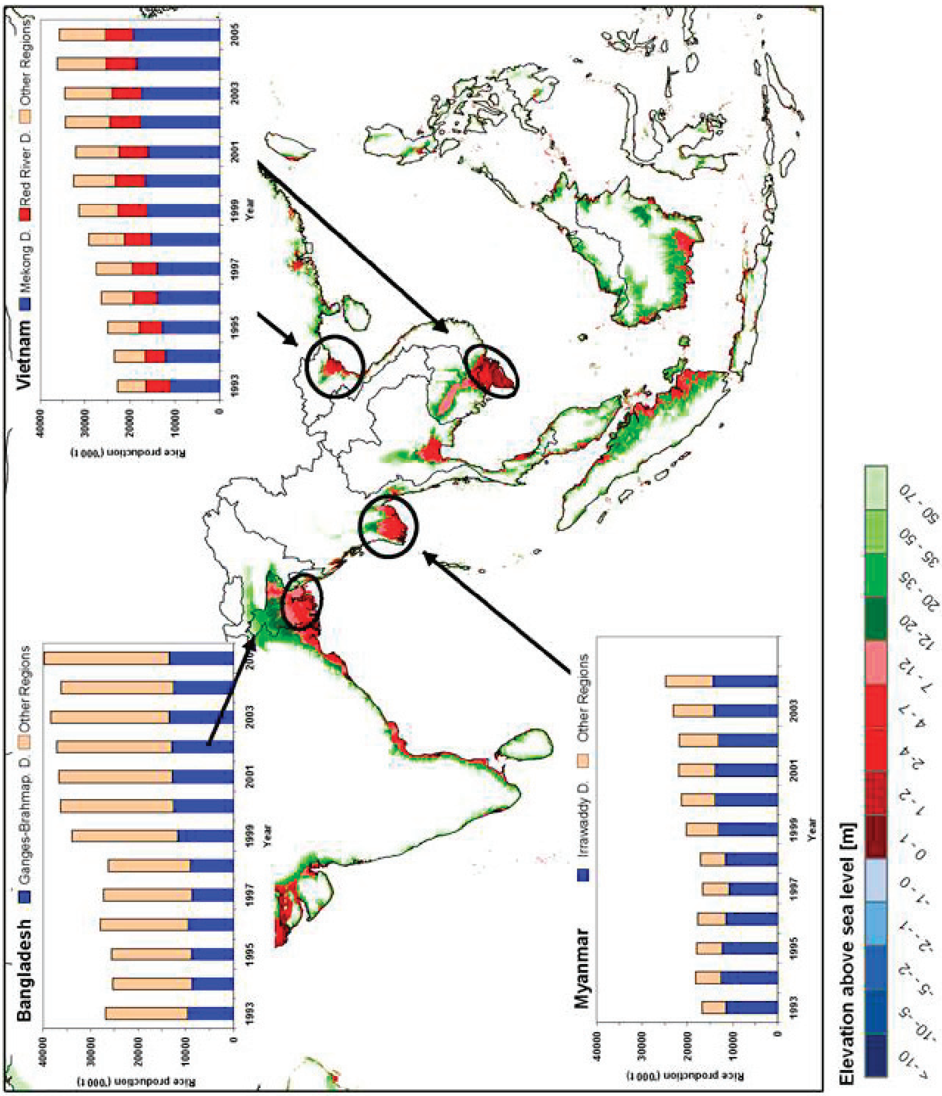

Fig. 1. Low-elevation areas in Asia and rice production data from deltas in Vietnam, Myanmar, and Bangladesh map drawn by K. Sumfleth (from Wassmann et al 2009b).

yields 54% of domestic rice production, with the Red River Delta adding another 17% (data from IRRI 2008; for the year 2005). Production growth in the Mekong Delta has been the driver for the steadily increasing rice production in Vietnam over the last decades. The Mekong Delta contributes to the vast share of rice exports of Vietnam, which account for 4.7 million tons of rice every year, making it the second-largest exporter worldwide (IRRI 2008). Thus, any shortfall in rice production in this area through climate change would not only affect Vietnam's economy and food security but also have repercussions on the international rice market. The deltas of Myanmar (Irrawaddy) and Bangladesh (Ganges-Brahmaputra) provide 68% and 34% of the national rice production, respectively. The rice produced in these deltas is essential for meeting national food requirements.

However, rising sea level may deteriorate rice production in a sizable portion of the highly productive rice land in deltas (Wassmann et al 2004). Higher sea levels impede gravitational river discharge and accelerate tides further inland to create—in combination with heavy rainfall—serious waterlogging and prolonged stagnant floods. Only a few low-yielding landraces in these areas are evolved to withstand such conditions. However, prospects for enhancing adaptation to these conditions using molecular tools are evident. Although flash floods during the vegetative stage can now be addressed by introgression of the *SUB1A* gene, additional genes are needed to increase the tolerance of stagnant flooding, that is, prolonged partial flooding with 30–60 cm of water depth, causing high mortality, suppressed tillering ability, reduced panicle size, and high sterility.

Seasonal climate forecasting in ENSO-affected regions

Scientific advances in meteorology and informatics have made it possible now to forecast drought within a seasonal time frame. Reliable forecasts could potentially be used to enhance drought preparedness nationally as well as to assist farmers in making more efficient decisions regarding their choice of crops and cropping practices. One such climatic indicator is the El Niño Southern Oscillation (ENSO) Index.

In unfavorable rainfed environments, precipitation variability is by far the most important factor for variability in crop production and agricultural economic risk. Detailed agricultural management strategies have been developed to cope with rainfall variability. These strategies are widely found in dryland agriculture: for example, improved water-use efficiencies of plants, diversification of farming systems, crop rotations, and fallow management practices. Recent developments in the application of seasonal climate forecasts in the agricultural sector suggest that there is large potential for enhancing agricultural risk management, thus enabling farmers to tailor management decisions to the cropping season (Hansen et al 2007, Meinke et al 2006).

Economic assessment of impacts

The rice plant will be affected by changing climate and rice growers will have to take those effects into account as they make management decisions, including varietal choice, planting months, and nutrient and water management. The biological effects of climate change on rice and the management choices of producers will result in changing prices, trade flows, and consumption patterns. A central climate change challenge for research for improving rice production systems is to incorporate the still uncertain effects of climate change into ongoing work on improving rice productivity.

In a recent study for the World Bank (Nelson et al 2009), researchers from the International Food Policy Research Institute (IFPRI) investigated the impacts of climate change on agriculture, beginning with the biological effects on crop productivity and tracing through market effects on production and consumption to the welfare consequences in developing countries. In this section, we summarize the results of that study, with an emphasis on the role played by rice production and consumption.

As mentioned above, changes in temperature and precipitation patterns will alter production opportunities for rice producers. Because of uncertainties in possible climate outcomes, our study used two climate scenarios. Both scenarios are based on the emission scenario SRES A2, which was input into two general circulation models, namely, those developed by NCAR (National Center for Atmospheric Research, U.S.) and CSIRO (Commonwealth Scientific and Industrial Research Organisation, Australia). However, substantial differences exist across these two climate scenarios (Appendix). For example, the NCAR scenario has substantially higher average maximum temperatures than does the CSIRO scenario. These maps illustrate qualitatively the range of potential climate outcomes with current modeling capabilities and thus indicate the uncertainty in the impacts of climate change.

The climate data were used with DSSAT software (a suite of crop models with a common user interface and data management system, see Jones et al 2003) to "grow" crops around the world with location-specific inputs of nutrient and management systems. Each crop is grown with 2000 climate and again with 2050 climate and the ratio calculated. Table 2 reports the purely biological effects of these climate change scenarios on rice productivity for selected regions of the world. For rainfed rice, the effects of both temperature and precipitation changes are included. For irrigated rice, Table 2 includes only temperature effects as irrigated crops are assumed to receive sufficient water. As stated above, however, the fertilization effect of CO_2 represents a major uncertainty for assessing future yields. This effect is described in current crop models through fairly simple response functions that do not reflect the rather complex interaction observed in the more recent experiments on CO_2 enrichment. Therefore, we have opted to list the results of the "no CO_2 fertilization" scenario in Table 2 to show the lower margin of conceivable impacts—irrespective of the unlikely nature of having no CO_2 effects at all. In Table 2, the effects of CO_2 fertilization (CF) on rice yields have been computed with an assumed atmospheric concentration of CO_2 of 369 parts per million (ppm) in both climates and with 532 ppm with the 2050 climate and no CF.

Irrigated rice yields show the greatest decline because irrigated rice is grown in more nearly optimal conditions so an increase in temperature stress has a greater relative effect than in rainfed conditions. However, the spatial units used in Table 2 comprise large entities that aggregate climatic zones with different degrees of vulnerability to temperature increase. The East Asia and Pacific region combines both Northeast Asian countries such as China, where rice grown in temperate conditions

Table 2. Yield changes for irrigated and rainfed rice under current climate and two climate change scenarios in 2050 with CO_2 fertilization (CF) and without CO_2 fertilization (No CF) effects (percentage change in relation to yields with 2000 climate).

Region	CSIRO No CF	NCAR No CF	CSIRO CF	NCAR CF
Irrigated				
East Asia and the Pacific	–13.0	–19.8	4.4	–1.1
South Asia	–15.5	–17.5	2.5	1.4
Sub-Saharan Africa	–11.4	–14.1	5.7	2.4
Rainfed				
East Asia and the Pacific	–4.5	–5.8	2.5	1.8
South Asia	0.1	2.6	8.5	10.2
Sub-Saharan Africa	0.1	-0.5	8.1	7.3

Source: Nelson et al (2009).

will be less seriously affected, with Southeast Asia, where the effects of higher temperatures are likely to be more serious. Rainfed rice is less affected by the climate change scenarios. Increased precipitation in both scenarios compensates in many places for higher temperatures, especially because rates of N fertilization are assumed to be relatively low in rainfed rice in many parts of the world.

In the next step, we calculated the implications of climate change for the availability and use of irrigation water. Both NCAR and CSIRO scenarios result in more precipitation over land than with no climate change in most parts of the world, so internal renewable water is generally enhanced under climate change. However, the CSIRO scenario has relatively small increases in precipitation as compared with the "wetter" NCAR scenario. Given that both water requirements and consumption are higher, the net effect on water supply reliability (expressed in the "irrigation water supply reliability index," see Nelson et al 2009) depends on the scenario used. Under the "wetter" NCAR scenario, the reliability of irrigation water will be improved, whereas it will deteriorate under the "drier" CSIRO scenario. On the other hand, extreme climate events, for example, those causing extended flooding/submergence of rice, are not really well captured in any of these climate models and subsequently are not properly reflected in the resulting climate change scenarios.

Finally, the IMPACT model—the International Model for Policy Analysis of Agricultural Commodities and Trade—was used to assess the impact of the two climate change scenarios on regional and global rice supply and prices. IMPACT was developed at IFPRI in the 1990s to represent a competitive world agricultural market for 30 crop and livestock commodities, including cereals, soybeans, cotton, roots and tubers, meats, milk, eggs, oils, sugar/sweeteners, fruits/vegetables, and fish (Rosegrant et al 2005). It is specified as a set of 115 countries and regions within each of which supply, demand, and prices for agricultural commodities are determined. IMPACT generates annual projections for crop area, yield, and production; crop demand for food, feed, and other uses; crop prices and trade; and livestock numbers, yield, production, demand, prices, and trade. Yield reductions of irrigated crops due to water stress are directly estimated in the IMPACT model using empirical relationships developed by the Food and Agriculture Organization (FAO) (Doorenbos and Kassam 1979), taking into account the growing demand for water outside agriculture as well as agricultural demands.

Table 3 reports the effects of climate change on rice production, accounting for both the changes in yield and changes in crop area induced by climate change. We have listed the three most relevant regions for food security as well as the global figures. Under "no climate change" scenario, rice production is projected to increase significantly in South Asia (by 49.1 million tons) and sub-Saharan Africa (by 10.8 million tons), whereas it will basically stagnate in East Asia/Pacific. However, South Asia and sub-Saharan Africa will suffer rather big losses under climate change: the projected climate change impact is 14–15% with almost no difference between the two scenarios. The climate change–related losses are lower in East Asia/Pacific, but may still impair food security given the relatively low production levels in 2050. Worldwide, rice production is projected to increase from 390 million tons in 2000 to 455 million tons in 2050 as long as the impacts of climate change are disregarded, but climate change will lead to relative production losses of 11.9% (NCAR) and 13.5% (CSIRO), respectively.

The direct and indirect effects of climate change on agriculture play out through the economic system, altering prices, production, productivity investments, food demand, food consumption, and ultimately human well-being. World prices are a useful single indicator of the effects of climate change on agriculture. Without climate change, IMPACT projects a 61% increase in rice prices in 2050 relative to the 2000 price. But climate change is likely to trigger even higher prices for rice. The simulation

Table 3. Climate change effects on rice production (million tons) in selected regions and the world; NCAR and CSIRO scenarios without CO_2 fertilization effect; numbers in parentheses denote percentage changes as compared to no Climate Change scenario (No CC).

Year/scenario	South Asia	East Asia/Pacific	Sub-Saharan Africa	World
2000	119.8	221.7	7.5	390.7
2050, No CC	168.9	217	18.3	455.2
2050, NCAR	144.7	199.4	15.6	401.0
	(–14.3%)	(–8.1%)	(–14.5%)	(–11.9%)
2050, CSIRO	123.8	176.9	13.3	346.9
	(–14.5%	(–11.3%)	(–15.2%)	(–13.5%)

Source: Nelson et al (2009).

results using both NCAR and CSIRO scenarios showed similar trends; in either case, the prices under climate change were approximately 35% higher as long as the CO_2 fertilization effect was not taken into account. This increment could be buffered to some degree by the CO_2 effect; the CF scenarios account for moderate price increases in the range of 13%.

Greenhouse gas emissions

Rice production plays a significant role in the global source strength of greenhouse gases (GHG). Anaerobic decomposition in rice paddies results in the release of substantial amounts of methane into the atmosphere. Although CH_4 is the most important component of the carbon footprint of rice production, the interactive nature of carbon and nitrogen cycles in rice fields requires consideration of the other GHGs, namely, N_2O and CO_2, in view of full global warming potential (GWP) accounting of all GHG involved.

Source strength of rice production

Methane. The magnitude and pattern of methane emissions from rice fields are mainly determined by water regime and organic inputs, and to a lesser extent by soil type; weather; management of tillage, residues, and fertilizers; and rice cultivar. Flooding of the soil is a prerequisite for sustained emissions of methane. Mid-season drainage, a common irrigation practice adopted in the major rice-growing regions of China and Japan, greatly reduces methane emissions. Similarly, rice environments with an insecure supply of water, namely, rainfed rice, have a lower emission potential than irrigated rice. Organic inputs stimulate methane emissions as long as fields remain flooded. In addition to management factors, methane emissions are also affected by soil parameters and climate.

In spite of considerable efforts to quantify methane emissions from rice fields, the estimates of this source strength are still attached to major uncertainties. Given the diversity of rice production systems, reliable upscaling of methane source strengths requires a high degree of differentiation in terms of management practices and natural factors. Modeling approaches have been developed to simulate methane emissions as a function of a large number of input parameters, namely, modalities of management as soil and climate parameters.

Figure 2 displays data obtained from the EDGAR database (Olivier and Berdowsky 2001, Olivier et al 2005), compiled with extended activity data from the National Inventories of GHG emmissions. The CH_4 rice map reflects distinct "hot spots" in China and India as well as in Southeast Asia. These hot spots in China, northwest India, Vietnam, and the Philippines correspond to areas with high abundance of rice fields and dominance of irrigated rice. Eastern India, northeast Thailand, and south Myanmar have a relatively high amount of rainfed rice (with a lower methane emission potential than irrigated rice), but the prevalence of rice as compared with other forms of land use marks these regions with high methane emission potential. Yan et al (2009) recently estimated CH_4 emissions from global rice field based on the Tier

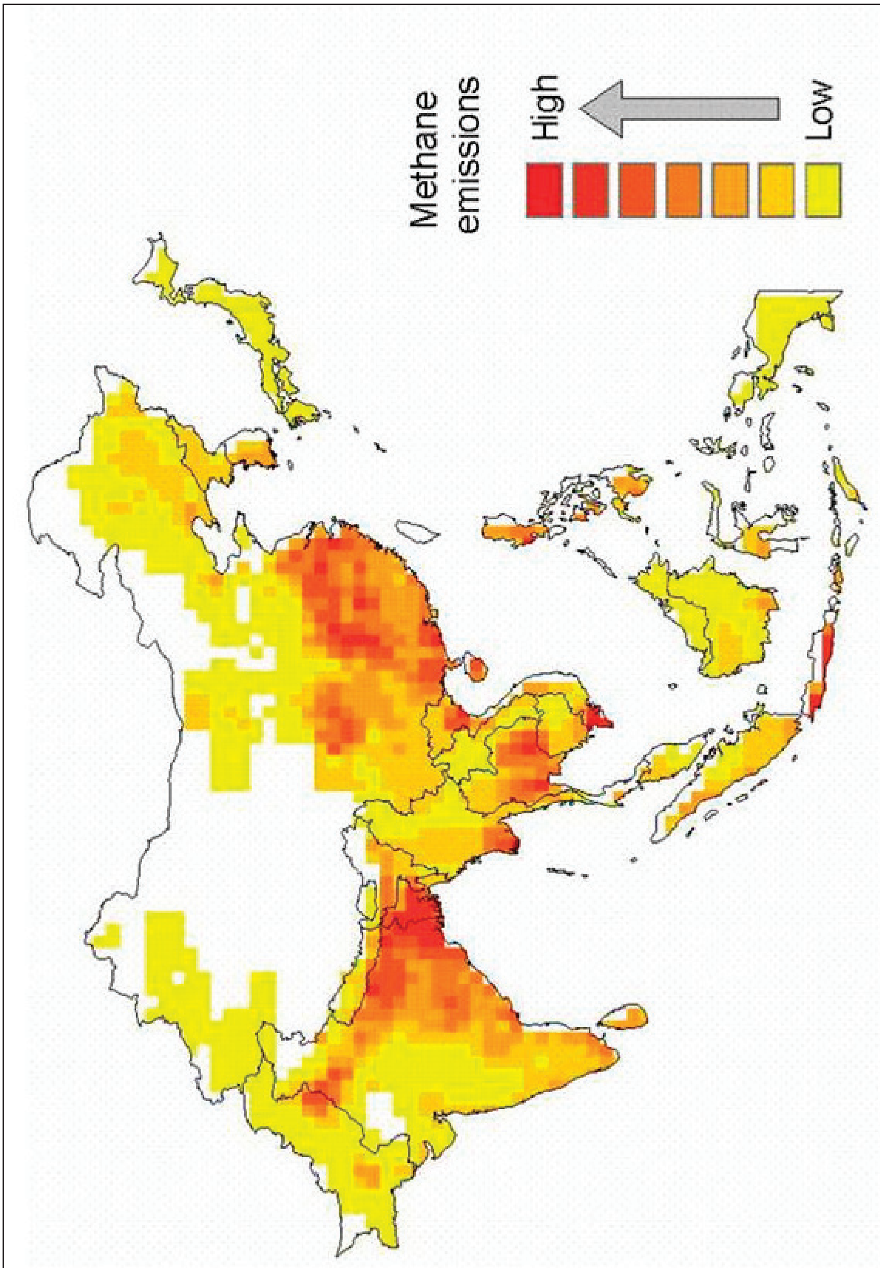

Fig. 2. Methane emissions from rice production in South, East, and Southeast Asia; classes correspond to low/high emissions per 1° grid cell and year derived from Emissions Database for Global Atmospheric Research (Olivier et al 2005). Data source: EDGAR VS.2 (www.mnp.nl/edgar/model/edgarv32/ghg/Methane.jsp). Map drawn by K. Sumfleth (Ortiz-Monasterio et al 2010).

1 method described in the 2006 IPCC guidelines (IPCC 2006) with country-specific statistical data regarding rice harvest areas and expert estimates of relevant agricultural activities. The estimated global emissions for 2000 were 25.4 Tg per year, which is at the lower end of earlier estimates and close to the total emissions summarized by individual national communications. These results are in line with other assessments of methane source strengths from rice fields. According to the latest summary by the IPCC (Denman et al 2007), rice fields emit 31–112 Tg of CH_4 per year, about 12–26% of the anthropogenic CH_4 sources, or about 9–19% of global CH_4 emissions (base years: 1983-2001).

Nitrous oxide. According to the latest IPCC summary (Denman et al 2007), arable lands emit about 2.8 Tg of N_2O per year, about 42% of the anthropogenic N_2O sources, or about 16% of the global N_2O emissions, but rice fields are not distinguished from upland fields. Early studies found N_2O emissions from rice fields to be negligible (e.g., Smith et al 1982). However, later studies suggested that rice cultivation was an important anthropogenic source of not only atmospheric CH_4 but also N_2O (e.g., Cai et al 1997).

The initial IPCC guidelines for compiling national GHG inventories use a default fertilizer-induced emission factor (EF) of 1.25% of net N input (based on the unvolatilized portion of the applied N) and a background emission rate for direct emissions from agricultural soil of 1 kg N/ha per year (IPCC 1997). Later, IPCC revised the EF for N additions from mineral fertilizers, organic amendments and crop residues, and N mineralized from mineral soil as a result of loss of soil carbon to 1% (IPCC 2007). These revised guidelines provide two standard conversion factors for determining nitrous oxide emissions based on fertilizer application—for flooded rice, 0.003 of the fertilizer N becomes nitrous oxide; for all other crops, the ratio is 0.01. However, there is no distinction as to crop and water management effects on N_2O emissions in the IPCC accounting procedure.

Carbon dioxide. Rice soils that are flooded for long periods of the year tend to accumulate soil organic matter (SOC), even with complete removal of aboveground plant biomass (Bronson et al 1997). Significant input of C and N is derived from biological activity in the soil-floodwater system (Roger 1996), and conditions are generally more favorable for the formation of conserved soil organic matter (Olk et al 1998, Kirk and Olk 2000). In China, it is estimated that the current C sequestration rate in irrigated rice cultivation is 12 Tg C per year and that these systems have induced a total enrichment of SOC storage of about 0.3 Pg C (Pan et al 2003).

Mitigating options

Technological approaches. Many mitigation options for GHG emissions through field management have been suggested and can be classified into four categories: changes in water management, organic matter applications, soil amendments, and others (Yagi 2002). Changing water management appears as the most promising option and is particularly suited to reducing emissions in irrigated rice production, that is, the rice ecosystem with the highest emission potential.

Securing a stable and adequate supply of water as in the past will become more difficult even for irrigated rice ecosystems because of the effects of climate change and competition from industry and domestic usage. Linked with this water resource issue, the mitigation options for the carbon footprint of rice fields through water management are worthy of attention.

Mid-season drainage or intermittent irrigation, which prevents the development of soil reductive conditions, is considered to be an effective option for mitigating CH_4 emissions from rice fields (e.g., Yagi et al 1997). A statistical analysis of a large data set from Asian rice fields indicated that, compared with continuous flooding, a single mid-season aeration can reduce average seasonal CH_4 emissions by 40%, and multiple aeration reduces them by 48% (Yan et al 2005). Li et al (2006) estimated that, despite large-scale adoption of mid-season drainage, potential was still large for additional methane reductions from Chinese rice paddies of 20% to 60% over 2000-20 with the DeNitrification and DeComposition (DNDC) model, a process-oriented model. Through the analysis, water management strategies appeared to be the most technically promising GHG mitigation alternatives, with shallow flooding providing additional benefits of both water conservation and increased yield.

However, mid-season drainage or reduction in water use can potentially increase N_2O emissions by creating nearly saturated soil conditions, which promote N_2O production (e.g., Zheng et al 2000). There are reports that mid-season drainage both increased and decreased the net carbon footprint of rice fields. Cai et al (1999) reported that the carbon footprint of N_2O emissions was even higher than that of CH_4 emissions from Chinese rice fields with mid-season drainage when large amounts of chemical fertilizer (364.5 kg N/ha) and farmyard manure (5 t/ha) were applied. Bronson et al (1997) found that the total carbon footprint of continuously flooded fields was lower than that of fields drained mid-season when no straw was applied, but it was higher when straw was applied. All in all, however, there seems to be broadening consensus that mid-season drainage decreases the net carbon footprint of rice fields judging from the data set accumulated in the past. According to an empirical model proposed by Yan et al (2005), mid-season drainage generally tends to be an effective option for mitigating net carbon footprint though 15% to 20% of the benefit gained by decreasing CH_4 emissions was offset by an increase in N_2O emissions. Further, Li et al (2004) reported that mid-season drainage reduces net carbon footprint compared with continuous flooding; 65% of the benefit gained by decreasing CH_4 emissions from rice fields in China was offset by an increase in N_2O emissions, as determined by the DNDC model. However, Yan et al (2009) estimated, based on the 2006 IPCC guidelines, that the increased global warming potential resulting from the increase in N_2O emissions was offsetting approximately only 2.7% of the reductions achieved through lower CH_4 emissions.

We can conclude that mid-season drainage has potential to be an effective option to mitigate the net carbon footprint of rice fields—especially when larger amounts of rice straw are returned to the soil. However, there is a risk that N_2O emissions offset the reduction in CH_4 emissions when N fertilizer is applied at a high rate. Thus, this modification of water management should preferably be coupled with efficient fertilizer application as a means to reduce GHG emissions—in addition to savings in irrigation water and fertilizer.

The drainage timing and span of conventional water management have been depending on farmers' empirical knowledge and customary practices. In order to provide farmers with specific criteria for draining and watering, from the viewpoint of saving water, the International Rice Research Institute (IRRI) has been developing and disseminating the alternate wetting and drying (AWD) irrigation management technique that provides farmers with specific criteria for soil water for judging the timing of watering to avoid imposing drought stress on rice plants (Bouman et al 2007). This AWD technique basically does not give any forced drainage to save water and reduces field water application by 15–20% without significantly affecting yield and increases the productivity of total water input (Tabbal et al 2002, Belder et al 2004).

The immense variability of environmental factors on the more than 150 million ha of annually harvested rice fields effectively defies blanket strategies to reduce emissions. Moreover, technological options in rice production have to remain economically viable under a rapidly changing environment—in terms of both socioeconomic development and environmental changes. To illustrate this approach, we present a case study encompassing the "policy angle," that is, a cost-benefit analysis of mitigation at the national scale.

Case study—country-wide mitigation in India. Indian agriculture alone accounts for approximately 5% of the global CH_4 budget. Nelson et al (2009) used field-level data collected by Pathak et al (2005) with two global land-use data sets to assess the costs and benefits from a mid-season drying.

Figure 3 plots the relationship between different management practices, namely, N application of urea and mid-season drying, on GHG emissions in India. The effects of mid-season drying on yield are minimal at 1.5–3.5% (Fig. 3A). However, this mid-season drying has a profound effect on methane emissions, as shown in Figure 3B. Even without nitrogen applied, methane is emitted as organic material from earlier crops that decay anaerobically. The addition of N stimulates more plant growth, and most of the plant decays, and, in an anaerobic environment, releases methane. With 120 kg of N applied to a continuously flooded rice field, methane emissions are 96 kg C/ha. (All results in this section are based on the molecular weight of the carbon in the CH_4 molecule.) With one drying, emissions drop to 66 kg C/ha; a second drying reduces emissions to 42 kg C/ha. In addition to methane reduction, mid-season drying slightly increases emissions of N_2O. These results are strictly applicable only to the research environment in which they were conducted; many farmers do not achieve these yield levels. However, we are interested in the *change* in yields and methane emissions with a change in management practice. We assume that the changes identified in this study are broadly similar to changes that could be achieved in farmers' fields.

Nelson et al (2009) used these data in IFPRI's IMPACT model to estimate methane and N_2O emissions from rice in India (Table 4). The combined emissions

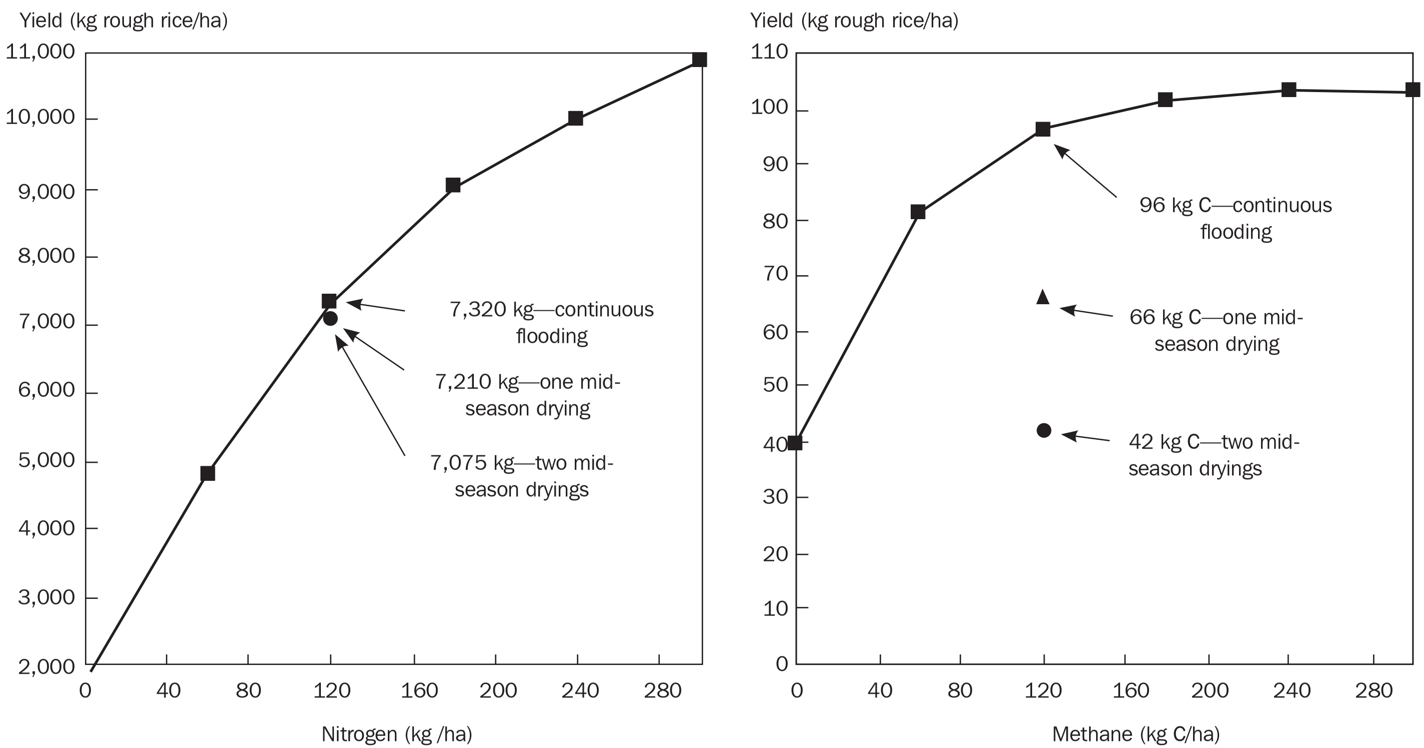

Fig. 3. Nitrogen yield curve (A) and methane emissions (B) in irrigated rice (data adopted from Pathak et al 2005).

Table 4. Effects of mid-season drying on irrigated-rice GHG emissions in India, 2000 vs. 2050, with conventional irrigation (continuous flooding) and single mid-season drainage (SMD).

Item	Year (unit)	2000		2050	
		Conventional irrigation	SMD	Conventional irrigation	SMD
Rice production	million tons	39.37	38.78	74.07	72.95
CH_4 emissions	million tons C	1.49	1.02	1.91	1.32
N_2O emissions	million tons N	0.029	0.03	0.037	0.038
C footprint	million tons CO_2e	74.7	60.9	95.8	78.2
Irrigated rice area	000 ha	15,530		19,925	

Source: G. Nelson, personal communication. Area and production growth rates are based on IFPRI IMPACT baseline estimates of September 2008.

of methane and N_2O in irrigated rice agriculture in 2000 result in 74.7 million tons of CO_2 equivalents (CO_2e). If all of this area used a single mid-season drying, CO_2e drops to 60.9 million tons, a decline of about 20%. The corresponding drop in rice production is 1.5%. The opportunity cost is US$1.20 per ton CO_2e, well below current carbon prices in European markets.

Outlook

Technological progress alone will be insufficient to cope with climate change, but research on germplasm improvement and crop management represents a pivotal component in climate policy. More than 800 million people in tropical and subtropical countries are currently food-insecure. Their situation is expected to worsen, and the number of food-insecure people is likely to increase as a consequence of the effects of climate change—unless drastic measures are implemented to increase their capacity to adapt to climate change.

The rice-cropping system is the economic backbone of many Asian nations and even a small decrease in productivity will imperil food security. Therefore, the system needs to be modified and diversified to increase adaptability to changing climate. Although developing more tolerant crop varieties is at the heart of adaptation measures, the efficiency of this approach can be increased significantly by geographic analysis of vulnerable regions, and regional climate modeling to identify temperatures or CO_2 levels above which major yield losses are experienced; then, site-specific adjustments in crop management can be made to optimize the production system. Several uncertainties that limit the accuracy of current projections on temperature increase, changes in precipitation patterns, and their geographic distribution need to be resolved. There are several ways (such as adjusting cropping calendars, introducing stress-tolerant rice cultivars, and water-saving techniques) by which the adverse impact of climate change can be mitigated, so that agriculture can cope with changing climate. There is a need to develop a policy framework for implementing adaptation options so that farmers can be saved from the ravages of climate change.

The scientific progress made in understanding the physiology of abiotic stresses and in the development of biotechnology tools has opened up promising opportunities for making a significant impact through improved technology. However, as the 2008 rice crisis demonstrated, agricultural research in general remains grossly underinvested in the developing countries of Asia. This is a cause for concern, not only for climate change adaptation and mitigation but also for promoting overall agricultural development.

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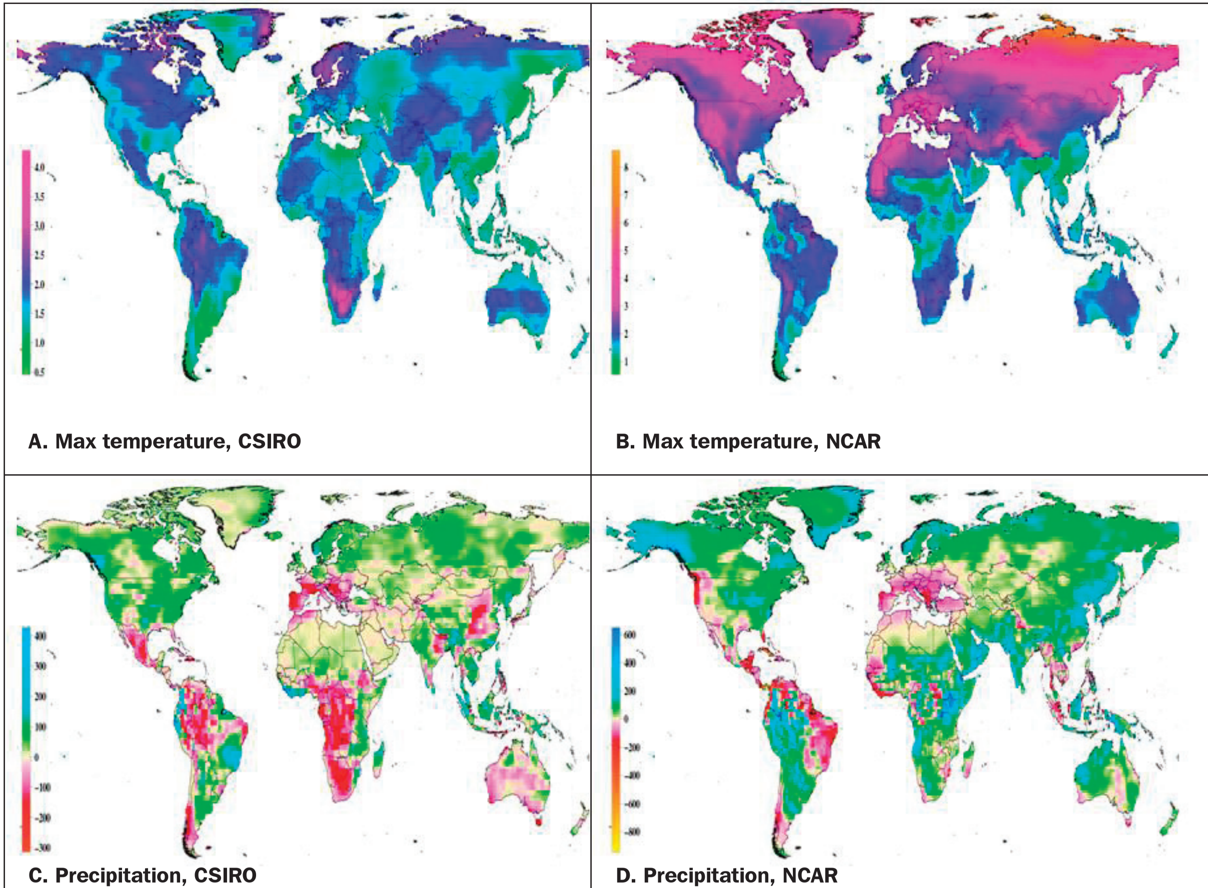

Appendix. Projected changes in average maximum temperature and precipitation, 2000-50, by CSIRO and NCAR scenarios, respectively.

Chapter 4.2

Technological opportunities for developing and deploying improved germplasm for key target traits

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Introduction

The world's first rice breeders were the farmers who domesticated Asian rice (*Oryza sativa*) from wild progenitors around 7,000 years ago, most probably in China (Fuller et al 2009). *O. sativa* may have been domesticated more than once from different strains of *Oryza rufipogon*, its immediate ancestor (Kovach et al 2007). As the seed was moved into different regions and growing environments, farmers selected different genetic strains that had advantageous new traits and were more adaptable to the different environments. The several hundreds of thousands of strains have captured valuable new genes and alleles (variant forms of the genes) that impart beneficial adaptive traits. A different domesticated rice, *Oryza glaberrima*, is cultivated in some parts of West Africa. While Asian rice has become the dominant rice species cultivated in Africa, breeders have crossed it with *O. glaberrima* strains to introduce new traits and develop New Rice for Africa (NERICA) rice varieties (Wopereis et al 2008).

The successful development and dissemination of improved varieties, mostly associated with the Green Revolution that started in the 1960s, are evidence of the extraordinary success of contemporary rice breeders, in this case using modern approaches to breeding. Rice yields have steadily increased over this period because of the increased use of fertilizers and cultivation of high-yielding varieties (HYVs) that can respond to them. Asian governments heavily promoted the semidwarf HYVs, and farmers in irrigated areas rapidly adopted them. Farmers in rainfed areas were less inclined to adopt these varieties, but some improved varieties were also developed that were suitable for them. One example, Mahsuri, a tallish variety developed from an indica/japonica cross, spread rapidly throughout India, Bangladesh, and Nepal. It has been replaced by its HYV descendent, Swarna, now grown on millions of hectares of rainfed lowland rice.

Just as evolution is open-ended, plant breeding is a continuous process, and many challenges face rice scientists to make further improvements in rice varieties. This chapter will highlight some of the looming problems and opportunities for breeding new rice varieties. Technological advances in the last two decades have provided powerful tools for developing new cultivars, but these have not yet shown their potential.

The major challenges of rice improvement

The commonly followed objectives of rice breeders include

- High grain yield and good agronomic properties
- Acceptable or superior grain quality
- Resistance to diseases and insects (biotic stresses)
- Resistance to abiotic stresses (drought, submergence, adverse soils and temperatures)

Rice scientists have devoted considerable attention to these traits for over half a century, yet they remain as relevant and challenging as ever in the 21st century. The high yield of the semidwarf cultivars, based on the *sd1* gene inherited from cultivars Dee-geo-woo-gen and I-geo-tze, has been incorporated into nearly every HYV grown. However, under tropical conditions, it has been very difficult to move beyond the yields obtained by the early semidwarf HYVs (Peng et al 1999). Yield per day has been greatly improved by developing early-duration varieties (Evans et al 1984), and some breeders continue to shorten the duration of cultivars to allow further intensification of rice cropping. However, bringing growth duration significantly below 100 days will usually entail a yield penalty.

Grain quality has been improved greatly compared with that of the original HYVs, and popular varieties such as IR64 and Samba Mahsuri (BPT 5204) have shown that it is possible to combine high yield with good grain quality. Some improved premium-quality varieties have also been developed, such as Pusa Basmati 1, that have aromatic grains. Rapid advances are being made in gaining a better understanding of what constitutes superior grain quality but the ultimate assessment is a cooking test by trained tasters and preference analysis in participatory varietal selection (PVS) schemes.

Remarkable advances have been made in identifying genes conferring disease and insect resistance, and many of these genes have been incorporated into HYVs. Notable examples are genes for bacterial blight and gall midge resistance. Despite this, many popular varieties being grown in tropical Asia are still susceptible to pests. The ability to rapidly deploy existing resistance genes into farmer-preferred varieties is still lacking. Furthermore, some problems such as blast and stem borer cannot be solved through the deployment of major gene resistance. In the case of blast, major genes usually do not confer durable resistance, and, for stem borer, major gene resistance has not been found.

Abiotic stress tolerance provides an example of recent advances that have been facilitated by improvements in phenotyping and molecular genetics. Submergence-tolerant varieties developed through incorporation of the *SUB1* gene (Xu et al 2006) are now being disseminated in flood-prone areas of tropical Asia. Salt-tolerant varieties have been very successful in the inland saline areas of eastern India as well as the dry-season coastal regions of India and Bangladesh. The identification of major quantitative trait loci (QTLs) such as *Saltol* (Bonilla et al 2002) should enable the development of salt-tolerant mega-varieties as with the *SUB1* case (Ismail et al 2007). Even a relatively intractable trait such as drought tolerance has begun to yield to determined efforts. Some improved drought-tolerant breeding lines have yields that are on a par with or above those of existing farmers' HYVs, and that yield 1–2 t/ha when these varieties collapse completely under drought stress. This very active area of research is expected to result in major gains in rice production in rainfed areas over the next decade.

So, the classical breeding objectives must remain at the core of rice breeding efforts, and should provide exciting discoveries and advances due to the application of improved molecular technologies. Changing social conditions as well as the consequences of global warming will also call for looking at new traits over the next 20 years. We would like to highlight some of the key challenges that should be addressed by rice improvement programs.

Higher yield potential

Increasing the yield potential of rice varieties has been surprisingly elusive considering the importance of this trait. Farmers frequently cite yield and grain quality as the two most important traits for rice varieties. However, many breeders have turned away from a primary focus on higher yields and have emphasized quality and resistances, traits that are often easier to measure and more amenable to genetic manipulation. One possible explanation is that modern tropical rice has reached its biological yield limit, and a major advance could come only from radical re-engineering of photosynthesis to turn the rice plant into a C_4 plant. The higher yields of hybrid rice would indicate that yield potential of inbreds can also be further improved. This might be possible in inbreds through a more systematic focus of direct selection for yield improvement in segregating generations of crosses instead of waiting until the advanced generations. A renewed focus on developing a more efficient plant type is being applied at IRRI to develop higher-yielding inbreds. Some of the molecular breeding approaches being used in maize and other crops that rely on recurrent selection are described below.

Higher yields have already been attained through hybrid rice technology, especially in subtropical regions such as in China and the southern United States. In tropical Asia, hybrids have not yet covered a large percentage of the area, and further improvements in yield of both F_1 hybrids and hybrid seed production are needed to make this more economical. For improving yield potential, an understanding of the basis of heterosis is necessary to select parents that will combine to form the highest-yielding hybrids. Genetic diversity between the parents is considered important to obtain the highest hybrid yields, and indica/japonica hybrids form the major basis for the highest yielding hybrids in China. However, in order to make practical use of these higher yields in diverse hybrids, the parents need to be improved in grain quality traits as well as in disease and insect resistance so that the hybrids will meet the requirements of farmers. In addition, the parents also need to be improved for necessary traits that will increase the yield of F_1 seed used for producing the hybrid crop.

Durable pest resistance

Many farmers must cope with yield losses for pests or absorb the added costs and risks of frequent pesticide applications because the varieties they are growing are not sufficiently resistant. Future research needs to focus on identifying new resistance genes and incorporating them rapidly into breeding programs. These genes should be transferred into varieties with high yields and good grain quality so that they will be readily taken up by farmers. Some of the major challenges for Asian rice breeders are blast, bacterial blight, tungro virus, brown spot, sheath blight, and false smut for diseases and brown planthopper, gall midge, and stem borer for insects. With aerobic rice cultivation, nematodes and soil-borne pathogens are also important.

Water shortage and excess

Climate change is likely to result in more weather extremes, with water deficits and floods becoming more frequent (Wassmann et al 2009). In addition, competition for water is increasing from nonagricultural users. Drought stress is a common problem of rainfed rice, and water shortages may also limit the area that can be irrigated. The area of irrigated rice can be maximized by water-saving approaches such as aerobic rice and alternate wetting and drying (AWD). Rice varieties can be developed that perform well specifically under these situations. In rainfed areas, drought is the most severe constraint that reduces yield. In dry years, drought also affects production on millions of hectares in irrigated areas where rivers, ponds, tanks, or reservoirs may be insufficient to irrigate the crop (Maclean et al 2002). In drought-prone areas, drought risk reduces productivity even in favorable years as farmers avoid investing in inputs when they fear crop loss (Pandey et al 2007). In the future, water deficit is predicted to be a major challenge for sustainable rice production (Wassmann et al 2009) and the intensity and frequency of drought are predicted to be aggravated due to the ongoing climate change process (Bates et al 2008). Under moderate to severe drought, drought-tolerant varieties can provide a yield advantage of more than 1.0 t/ha, while maintaining high yield under irrigated situations. They can be cultivated under both direct-seeded and transplanted systems depending upon the initial rain received. They will not only provide farmers with sustainable yield in years of drought but also encourage them to apply higher inputs in favorable years, leading to a further productivity increase in drought-prone areas.

On the excess-water side, submergence-tolerant rice is a very effective way to deal with flash flooding (temporary submergence of up to 2 weeks). This must also be combined with tolerance of water stagnation. Current climate models predict higher increases in sea-water levels than originally anticipated (Bamber et al 2009). This will result in extensive inundation of coastal areas. Cultivars that combine tolerance of flash flooding and water stagnation need to be developed for these situations. Tolerance of salinity will also be needed in many environments. There seems to be no known barrier to combining tolerances of these different abiotic stresses.

Temperature extremes

Low-temperature tolerance is currently an important breeding objective in temperate areas and the high-elevation tropics. In addition, dry-season cultivation in the subtropics (boro rice) has spread rapidly in countries such as Bangladesh, and this crop is subjected to low-temperature stresses in the early part of the season. Considerable variability for tolerance exists in rice but it has not been exploited very much in the subtropics. High-temperature extremes cause sterility at the anthesis stage and result in poor grain filling and quality during ripening. This is currently not considered a major problem in most rice-growing environments. However, with global warming trends, it is expected to assume greater importance. High temperatures may also interact with drought stress to cause more yield losses. Tolerance for high temperature during anthesis has been identified and the genetics is now under study.

Improved cooking and nutritional quality

Standards of rice grain quality are generally specific to a region or ethnic group. Many or most of the popular varieties being grown widely by farmers have good grain quality that is desired by consumers. It is essential that all new varieties introduced match the quality requirements so that they will be accepted by farmers, millers, and consumers. Future research should focus on developing simple chemical or genetic tests that can be used to measure the quality of a large number of breeding lines when taste tests are not feasible. More affluent rice consumers demand premium-quality rice such as Basmati or Thai Jasmine varieties, and farmers usually receive a higher price for these varieties. In addition to cooking and appearance quality traits, nutritional quality has become an important rice breeding objective (Bouis and Hunt 1999, Welch and Graham 2004). In addition to Golden Rice with high vitamin A, rice varieties can also be improved for higher iron and zinc content in the grains, among other desirable micronutrients (Stein et al 2007).

Direct seeding

Transplanting is an effective crop establishment system, but it is also very laborious and the use of direct seeding is spreading. Rice varieties developed under a transplanting system can also be used for direct-seeded rice production. However, some traits are thought to be very beneficial for direct-seeded rice production, including seedling and vegetative vigor, less profuse tillering, and anaerobic germination (the ability to germinate under flooded conditions). These traits are now being addressed in breeding programs that focus on direct-seeded rice (Mishra et al 2008).

Overview of present and future rice breeding methods

An effective breeding program must start with carefully developed objectives, and these objectives will depend on a careful analysis of farmers' needs and deficiencies of existing rice varieties (Jennings et al 1979). In order to make progress in improving these traits, genetic variation must exist for them. The breeder must therefore begin with the development of a plant population that is segregating for genes that affect the objectives being addressed. In most breeding programs, this is done by hybridization of two or more complementary strains that differ in the traits under consideration. Once a segregating population is developed, superior plants are selected in each generation based on their appearance in the field and based on other data that are collected in screening nurseries or chemical tests. Seed harvested from superior plants is planted in a progeny row in the following generation. In this pedigree nursery, each row is a family of genetically related plants, and only families with superior characteristics will be selected for the next generation.

Most large breeding programs will make a hundred or more crosses in a season and, in the segregating generations produced, only a few plants will have the desired combinations of favorable genes. The probability of identification of superior plants is dependent on the number of plants that can be grown and assessed. It would not be unusual to have half a million or more F_2 plants being grown, with tens of thousands of single-row families evaluated in the pedigree nursery. By the time the fixed lines are developed, a few hundred of these may be deemed worthy of more advanced testing. Some breeders modify this procedure by using a "bulk" method, in which selected plants are combined and sown as one plot in particular generations.

These few hundred fixed lines are grown in larger plots in an observational yield nursery, and the best entries are advanced to replicated yield trials (RYTs). Because the target environments are often heterogeneous, and an experiment station does not fully represent this variability, the best entries in the RYT should be advanced to multilocation yield trials, which are required for determining which lines will be recommended as new varieties. At this stage, it is also common to begin evaluation with farmers, especially for rainfed situations (Courtois et al 2001). In PVS experiments, a few varieties are evaluated under farmers' field conditions to get feedback on which are the most promising lines for promotion as new varieties.

The backcross procedure can be used when a single variety is highly desirable and a breeder wants to enhance the chance of recovering plants close to this variety in the progeny. The backcross breeding method involves making serial crosses back to the variety (the recurrent parent) so that only one or a few genes or chromosomal fragments are transferred into that variety. Backcross breeding is now becoming more popular with the use of DNA markers for selection (described below).

Although plant breeders have made significant progress using conventional breeding methods, the past 20 years have seen molecular markers gain prominence in breeding programs.

The breeding methods described above rely on visual inspection and direct measurement of important traits. In the past 20 years, breeders have begun to use DNA markers for the application of marker-assisted selection (MAS) in breeding programs. These markers are used to map traits of interest on rice chromosomes, and provide information on genetic relatedness, linkage to important traits, and detection of donor introgressions in segregating populations. In the end, the usefulness of integrating molecular markers into a breeding program will depend on how well the markers can replace phenotyping (i.e., direct measurement of the trait on the plants), in terms of both cost-effectiveness and their ability to predict performance under different environments. Although great efforts have been invested in mapping genes and in developing marker techniques, only recently have markers become routinely used in major breeding programs, as evidenced by the successful release of the first generation of MAS-bred varieties from both the public and private sector. A number of strategies are now available to incorporate molecular tools into a rice breeding program to increase the efficiency and power of selection. Combining multiple genes, such as disease resistance genes, is a common practice referred to as "gene pyramiding," and this is facilitated by MAS. For example, gene pyramiding has been successfully used in rice to combine multiple genes for bacterial leaf blight, as well as resistance genes for other pests and diseases (for a review, see Collard and Mackill 2008).

Although early success was made with mapping genes for qualitative (major gene) traits, many traits in rice breeding are quantitative traits showing a normal distribution, due to control by multiple genes and environmental interactions. Mapping QTLs, which are chromosomal regions that contain a gene or genes contributing to a trait phenotype, requires comprehensive genetic maps to assign a phenotypic effect at markers near the QTL (Tanksley 1993). Numerous QTL studies have led to an explosion in the number of QTLs mapped in rice for a multitude of traits, with more than 8,000 QTLs now available in the online Gramene database (Liang et al 2008, www.gramene.org). Although dozens of QTLs are mapped for each major trait, the successful integration of QTLs into MAS programs has been more elusive, probably because many traits are controlled by multiple small-effect QTLs, often complicated by environmental interactions and/or differing genetic background effects. However, progress has been made with the transfer of single large-effect QTLs in rice, such as the use of the QTL *SUB1* to provide submergence tolerance to mega-varieties (Neeraja et al 2007, Septiningsih et al 2009). For smaller QTLs, new methods have been developed and applied in maize for assembling the desired QTLs into superior genotypes. The method referred to as marker-assisted recurrent selection (MARS) and an alternative approach designated genome-wide selection (Bernardo 2008, Mayor and Bernardo 2009) are being used to increase the efficiency of maize breeding. These methods will be applied in rice with the recent reductions in cost of marker analysis.

In drought, recent research on direct selection for grain yield under drought in populations derived from two parents differing significantly for drought tolerance has identified major QTLs with a large and consistent effect on grain yield under drought (Bernier et al 2007, Kumar et al 2007, Venuprasad et al 2009). These individual QTLs show the effect only under drought and contribute to more than 20% of the mean grain yield without any adverse effect under irrigated situations. An effective strategy to achieve a significant yield advantage of more than 1.0 t/ha under drought would require pyramiding of two to three QTLs in the background of popular varieties.

Although selection using closely linked markers for major genes and QTLs is the mainstay of MAS, a refinement of this strategy is to target the genes themselves for marker development. Intense research efforts around the world are focused on dissecting the molecular mechanisms and genetic pathways underlying key traits in rice—leveraging the value of the complete genome sequence for gene discovery and functional analysis. One common justification of the massive research investment in rice functional genomics is that the end result will empower more efficient strategies for molecular breeding. Thus, genomics-assisted breeding promises to apply discoveries from mutant analysis, DNA microarrays, QTL cloning, and allele mining to develop more precise molecular tools for crop improvement (Leung 2008, Varshney et al 2005). The most intuitive way to do this is to target a functional nucleotide polymorphism, which is a change in a gene that causes the desired phenotype, for the development of functional markers (Andersen and Lübberstedt 2003). By relying directly on the causal polymorphism, these "perfect" markers will be diagnostic of the favorable allele, since they will always co-segregate with the trait phenotype. For example, once the gene controlling aroma in rice was cloned, the sequence polymorphisms that led to increased aroma were identified and developed into a perfect marker for fragrance in rice (Bradbury et al 2005). As more genes controlling key traits in rice are characterized, there will be more opportunities to mine superior alleles from germplasm collections and to develop functional markers for more precise and efficient marker-assisted selection.

The successful implementation of these MAS strategies is dependent on having an efficient and robust genotyping system in place (Collard et al 2008). For many years, simple sequence repeats (SSRs) have been the marker system of choice because of high polymorphism rates and the ability to run them on inexpensive gel electrophoresis equipment found in most labs. However, the routine integration of MAS into modern breeding programs will require high-throughput genotyping platforms that can handle large numbers of samples at a low cost. Thus, a new generation of markers based on single nucleotide polymorphisms (SNPs) is now rapidly overtaking SSRs due to new SNP genotyping platforms that offer multiplexed sets of markers for different applications. Efforts are being made in the rice community to develop functional SNPs for foreground selection, to optimize 384- or 1,536-plex SNP chips for low-resolution genome scans, and to develop high-resolution SNP chips with >40,000 SNPs for association genetics studies. As these genotyping tools are made more accessible to rice breeders, the full potential of MAS in mainstream breeding programs will finally be realized.

Another field of molecular breeding relies on transgenic technology to introduce novel genes or alleles for crop improvement. Generally, if there is enough variation in the gene pool for the trait of interest, a MAS strategy will be preferred to avoid the inconveniences of producing and commercializing genetically modified (GM) crops. Although rice transformation is now routine, major hurdles for transgenic crops still exist, including the great expense for deregulation of a transgenic event and lingering concerns with public acceptance of GM rice. Nonetheless, there are a few traits for which going the transgenic route makes sense, such as biofortification of rice grains with essential nutrients that are missing from natural rice. For example, transgenic "Golden Rice" is moving forward with higher pro-vitamin A content, which promises to help alleviate vitamin A deficiency in regions with high rice consumption (Paine et al 2005). In other cases, such as drought tolerance, transgenic approaches are being pursued at the discovery phase, under the assumption that, by the time useful GM varieties are developed, the regulatory environment and levels of consumer acceptance will be improved.

Molecular markers for upgrading mega-varieties

Mega-varieties are varieties that are popular among farmers and are planted on large areas, usually more than 1 million ha. Farmers tend to keep planting these proven varieties and often hesitate to adopt new varieties because these mega-varieties have excellent combinations of desirable characters such as grain quality and adaptation to the local environment and cultural expectations (Collins et al 2008, Jena and Mackill 2008). It thus makes sense to upgrade mega-varieties for any lacking traits instead of replacing them completely with a new variety. However, this strategy is just one out of many breeding strategies that can be applied in the varietal improvement process. Multiple breeding strategies can complement each other to fulfill various needs and niches in different breeding programs.

With the incorporation of markers, a backcrossing strategy can be implemented more efficiently. Thus, marker-assisted backcrossing (MABC) can be used to rapidly and precisely introduce major QTLs or genes for any trait of interest. Using this strategy, the number of backcross generations used in the classical backcrossing method can be reduced to two or three backcrosses followed by selfing, and several examples of MABC for different traits have been reviewed (Collard and Mackill 2008). The key benefit is that this strategy can be used to shorten the time required in releasing a new variety.

Recently, the submergence-tolerance locus *SUB1* has been successfully introduced into six mega-varieties—Swarna, Sambha Mahsuri, CR1009 (Savitri), BR11, IR64, and Tadokam1 (TDK1)—within two to three generations of backcrossing followed by one selfing using the MABC strategy (Septiningsih et al 2009). Once these initial submergence-converted varieties were available, the conversion of new popular varieties became even shorter: in this case, needing just one backcross followed by selfing, when these new converted varieties were used as submergence-tolerant donors and the recipients were closely related to one of the donors. However, to ensure that the desired plant can be obtained in a BC_1F_2 population, larger populations need to be used. This strategy was recently used in the conversion of Ciherang-Sub1, a popular variety from Indonesia.

Now that many major QTLs have been fine-mapped and isolated in near-isogenic lines (NILs), these represent opportunities to rapidly combine multiple QTLs into the same background. For example, early success was made in pyramiding *Xa* resistance genes for bacterial blight (BB) disease. New MABC lines are now being developed for abiotic stress tolerance for salinity tolerance (*SALTOL*), phosphorus deficiency (*PUP1*), drought, and tolerance of flooding during germination (anaerobic germination, AG). These QTLs can be pyramided as needed, such as *SUB1* + *SALTOL*, and *SUB1* + AG, or combining several QTLs that are involved in one trait, such as in BB. However, the number of QTLs or genes that can be combined must be taken into careful consideration since the more QTLs or genes to deal with, the more complex the selection process and the greater likelihood of encountering negative linkage drag.

One potential downside of the use of MABC to upgrade mega-varieties is that it may further encourage the spread of one or a few varieties over large areas, to the detriment of maintaining a diversity of varieties. This could be of concern if the variety became susceptible to a devastating pest and needed to be rapidly replaced. However, MABC can also be used to introduce valuable genes into a wider range of varieties that would encourage farmers to maintain varietal diversity. In addition, there are many examples of a wide use of rice mega-varieties without major pest problems.

Innovative approaches for the dissemination of improved varieties

New varieties are now being produced more rapidly with advances in genetics and molecular breeding. With improved efficiency of rice breeding procedures such as MABC, it is now possible to develop a new variety in less than half of the time required by classical breeding programs. However, official release and dissemination of new varieties remain bottlenecks for delivering improved varieties to farmers. In view of this, it is essential to gear up the seed system to ensure that a variety reaches end-users (farmers) in the shortest possible time to have full impact. This will involve prerelease seed multiplication and varietal promotion, improved and faster varietal evaluation and release systems, and rapid scaling up of seed production and dissemination to farmers.

Dissemination of a new variety is often quite slow, particularly if it is targeted for an ecosystem dominated by a mega-variety. A large number of varieties released never reach farmers' fields. New approaches currently being deployed for promoting rapid dissemination consist of the following essential elements.

Participatory varietal selection

PVS is the procedure for the evaluation of new rice breeding lines by farmers, both on the experiment station and in their own fields. PVS is done in farmers' fields as researcher-managed (i.e., "mother") trials or farmer-managed ("baby") trials. In researcher-managed trials, a set of varieties is planted in farmers' fields under the supervision of a researcher, and male and female farmers are invited to visit the trials and rate the varieties. In farmer-managed trials, the top two to three best-performing varieties are planted in larger plots under the farmers' own management practices and compared with the farmers' existing varieties. PVS is a simple way to learn which varieties perform well on-station and on-farm. The chances of adoption of a variety selected though PVS are much higher than by the conventional system in which varieties are selected based only on experiment station results. It is also a method to make farmers aware of promising varieties well in advance of their release.

Faster release of MAB-generated varieties

In general, varietal evaluation involves at least one year of an initial varietal trial (IVT) and two years of advanced varietal trials (AVTs). DUS (distinctiveness, uniformity, and stability) testing and agronomic trials may involve additional years of testing or can be conducted simultaneously with AVTs. Data from all these trials are required for preparing the proposal for varietal release. In cases in which a new character is introgressed using MABC into a variety already grown by farmers, all these trials are not necessary because the original variety is already popular and well adapted to the area. For these varieties, a few countries have reduced the requirement to one year of AVT or agronomic trial, thereby reducing the time necessary for release. The main objective of evaluation is to determine whether the upgraded mega-variety is equal to the original variety in all traits except for the one for which it was improved.

Generating awareness

Awareness generation is most essential for rapid diffusion, which in turn creates seed demand and catalyzes seed multiplication. Therefore, it is essential for a promising line to go for awareness generation simultaneously with varietal evaluation. PVS partly serves this purpose. PVS, as an awareness generation strategy, can be made more effective by organizing field days at PVS sites to make a larger number of farmers aware of new material that is in the pipeline. Different pre- and/or postrelease varietal awareness generation strategies are field demonstrations, field days, farmers' fairs, media coverage (newspapers, TV and radio programs), documentaries, roadside dramas, etc.

Production and marketing of seeds through multiple channels

Formal institutional sources were the main channels for producing and marketing of seeds of improved varieties during the Green Revolution period. However, the private sector is now increasingly entering seed markets (Tripp et al, this volume) and is becoming an important player in the overall provision of seeds. Similarly, nongovernment organizations (NGOs) and farmer seed cooperatives are also playing bigger roles in such provisioning of seeds, more so in stress-prone areas where the private sector may have less incentive to operate. There are clear opportunities now to connect these different channels for a faster and smoother flow of high-quality seeds. For example, linking up with poverty alleviation schemes/mega-schemes and projects of government (e.g., National Food Security Mission and Rastriya Krishi Vikas Yojna in India) and nongovernment organizations (e.g., Catholic Relief Services, Sir Dorabji Tata Foundation, WWF, etc.) is seen as an effective strategy for the dissemination of stress-tolerant rice varieties in India.

Demonstration in farmers' fields linked with farmer-to-farmer dissemination

This is an effective strategy for both pre- and postrelease dissemination of a variety. Rather than emphasizing the production of a larger area of the new variety at a few sites, the strategy is to "inoculate" a larger number of sites with the new variety. During the next season, it is essential to inoculate newer sites, while letting the variety spread by farmer-to-farmer diffusion at the sites visited in the previous season. The usual "minikit" approach, which involves the provision of small quantities of improved seeds to farmers, can be an important approach for such "inoculation." This strategy is seen to be very effective for the spread of Swarna-Sub1 in the states of Uttar Pradesh and Orissa in India and in some districts in northern Bangladesh.

Conclusions

Rice breeding has been a highly successful endeavor and will continue to offer many opportunities for improving the productivity and profitability of rice farming, as well as offering rice consumers a higher-quality product. The advances in genetics will provide many new tools and allow breeders to make precise modifications of the genetic makeup of existing varieties to improve them for key traits. Breeders in the future will manipulate specific genes and assemble them in the combinations that lead to the optimum genotype (Peleman and van der Voort 2003, Yin et al 2004). However, for the foreseeable future, these new breeding methods will not completely replace those that have been used to develop existing popular varieties, but will be complementary to them. In order to capitalize on the advances in developing improved varieties, new strategies that involve various formal and informal organizations along the seed chain, including the private sector, are needed for promoting the rapid dissemination of these varieties to farmers.

The Consultative Group on International Agricultural Research centers responsible for rice breeding in Asia, Africa, and Latin America are IRRI, AfricaRice, and the International Center for Tropical Agriculture (CIAT). They have recently developed plans for a Global Rice Science Partnership (GRiSP), which will focus efforts of international centers, national agricultural research and extension systems (NARES), and advanced research institutes to address the problems facing rice-growing countries in meeting the increasing demand for rice over the next 25 years. Varietal improvement activities will include

- More precise targeting of rice breeding to key environments and market segments;
- Development and use of high-throughput marker applications in rice breeding programs;
- Wider use of interspecific crosses;
- Breeder-friendly decision tools for the public and private sector;
- Sources of improved quality and pest resistance;
- New, global research networks as a key strategy for achieving stable disease resistance in rice;
- A new generation of "climate-change-resilient," stress-tolerant rice varieties with combined traits;
- Renewed efforts to break the yield barrier in rice through a fine-tuned ideotype breeding approach, combined with advanced multienvironment testing;
- Breeding programs for direct seeding and conservation agriculture;
- A new generation of hybrids with higher yield, better quality, and higher seed yield; and

- Recurrent selection for physiological traits that confer higher yields, and attention to yield evaluation earlier in the breeding process.

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Notes

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Positioning rice research globally: investments, institutional arrangements, and emerging challenges

Nienke Beintema, David Raitzer, Achim Dobermann, Carl Pray, Luis Sanint, and Marco Wopereis

Introduction

Policymakers are increasingly recognizing that greater agricultural research investment is essential to increase agricultural production to the levels necessary to feed a growing world population. In addition, more investments in agricultural research are required to address emerging challenges such as adaptation to climate change, increasing weather variability, water scarcity, and increased price volatility in global markets. All these general issues apply to rice research as well. But, since the early 1990s, public investment in rice research in developing countries has not kept pace with the growing demand for this food crop. Only recently, and mainly as a result of re-emerging food security concerns, investments at national and international levels have increased and may slowly approach the levels needed to sustain rice food security.

Agricultural R&D has seen an increasing diversification of actors involving strong government agencies in countries such as China, India, and Brazil, and a strong international component through the research activities of the international agricultural research centers (IARCs) of the Consultative Group on International Agricultural Research (CGIAR), particularly the International Rice Research Institute (IRRI), the Africa Rice Center (AfricaRice), and the International Center for Tropical Agriculture (CIAT). In addition, an increasing number of interactions across different actors have been set up, for example, through formal research partnerships or through contractual relationships among the public and private sector. Breeding of improved rice varieties worldwide was dominated by the public sector, with a limited role of the private sector. However, in recent years, private companies have begun investing in rice breeding. This increased private-sector role has led to the development of a number of public-private partnerships. With these recent developments in investments and institutional arrangements, the main future challenge for the IARCs is to refocus their research on those strategic areas in which they can play a leading role while ensuring strong linkages with research activities by the public sector, civil society organizations, and the private sector.

This chapter presents a detailed overview of these recent developments in global and rice R&D investments and institutional arrangements and also addresses the establishment of various new partnership arrangements. The chapter will also provide economic evidence that there is indeed a need to further increase the investment levels for rice research. The chapter will conclude with a forward-looking section that addresses the various future challenges for global agricultural research, and rice research specifically.

Global patterns in agricultural research investments[1]

General patterns in public agricultural research[2]

The role of the agricultural sector—and agricultural research specifically—as the engine of economic growth and poverty reduction has received increasing attention in recent years after a long period of neglect. This neglect resulted in declining growth rates in agricultural R&D investments at both the national and global level (Fig. 1).[3] Agricultural R&D investments in the low- and middle-income countries grew by an average of about 3% per year during 1981-2000, or about one-half the annual rates during the second half of the 1970s. During the 1990s, growth further slowed, with

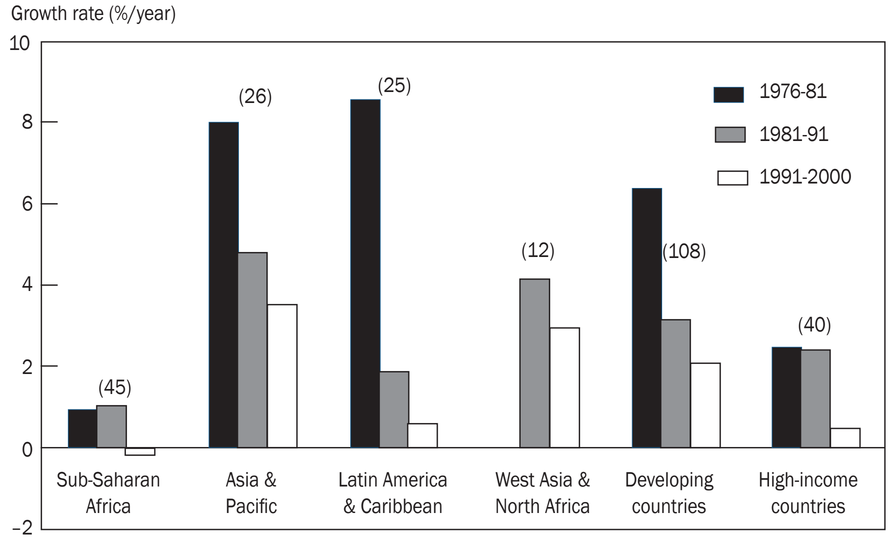

Fig. 1. Annual growth rates in agricultural R&D spending, 1976-2000. Sources: Beintema and Stads (2010) based on ASTI data sets (www.asti.cgiar.org) and other secondary sources.

[1]Based on Beintema and Stads (2010) and Beintema and Elliott (2009). Underlying data sets are available on the ASTI Web site (www.asti.cgiar.org).
[2]Public is here defined as government, higher education, and nonprofit sectors, excluding private for-profit businesses.
[3]The regional totals refer to developing countries (defined as low- and middle-income countries) only and exclude high-income countries such as South Korea in the Asia-Pacific region and Israel and Kuwait in the Middle East and North Africa region. The number of countries included in the regional totals is shown in parentheses. These estimates exclude Eastern Europe and former Soviet Union countries. Estimation procedures and methodology are described in Pardey et al (2006) and various ASTI regional reports available at www.asti.cgiar.org.

most of the growth occurring in the Asia-Pacific region. The latter was largely a result of high growth in agricultural R&D spending in the two largest countries, China and India (annually 5.3% and 5.8%, respectively, during the two-decade period). In contrast, spending in sub-Saharan Africa grew, on average, by only 0.6% per year during 1981-2000.

Public agricultural R&D, however, has become increasingly concentrated in just a handful of countries (Pardey et al 2006). The top five countries in terms of agricultural R&D spending, the United States, Japan, China, India, and Brazil, spent 48% of total global public agricultural R&D. Meanwhile, about 6% of the agricultural R&D investments worldwide were made in 80 (mostly low-income) countries that combined had a total of more than 600 million people and accounted for 14% of the world's agricultural land area. A knowledge divide between Asia's rich and poor countries and the scientific "haves" and "have-nots" is becoming more and more visible. During the period 1981-2002, especially in the latter decade of the period, China, India, Malaysia, and Vietnam realized impressive agricultural R&D spending growth. But, other countries such as Pakistan, Indonesia, and Lao PDR exhibited sluggish and at times negative growth, largely because of the Asian financial crisis, the completion of large donor-financed projects, or high rates of inflation. Recent data for Latin America and sub-Saharan Africa also show a similar divergence between some countries with declining spending levels, stagnating growth in others, and a substantial increase in spending in others. In Africa, however, this divide appears to be less consistent, in part because of the donor dependency of many countries as well as the erratic nature of government and donor support to agricultural research over the years.

Although data on global public investment patterns since 2000 are still unavailable, more recent data collected by the Agricultural Science and Technology Indicators (ASTI) initiative show that investments continued to grow in China and India (Fig. 2). Agricultural R&D expenditures in Latin America and the Caribbean rebounded in recent years following a period of contraction during the late 1990s, which was mostly due to a financial crisis in some Southern Cone countries.

Government commitments in a number of larger countries in terms of agricultural research investments have increased in recent years. China's public agricultural R&D spending continued to increase after 2000 in inflation-adjusted terms: in 2007, it totaled PPP US$4.3 billion, which is close to twice its 2000 total of $2.3 billion (both in 2005 prices). This translates to a growth rate of about 10% per year during 2000-07 (Chen and Zhang 2010). During the second half of the 1990s, total spending of Embrapa, Brazil's leading agricultural R&D agency, contracted considerably. Since 2001, total spending has remained fairly constant, although levels remained erratic from one year to another. Brazil's total spending, however, is expected to increase substantially during the next few years as a result of increasing budget allocations earmarked for Embrapa to reach the same level as its budget during 1995-96. In sub-Saharan Africa, Ghana and Nigeria have seen a substantial increase in total government agricultural R&D spending for 2000-08, while spending in Kenya and in many francophone West African countries contracted or stagnated since 2000, a trend continuing from the 1990s (Beintema and Stads 2010).

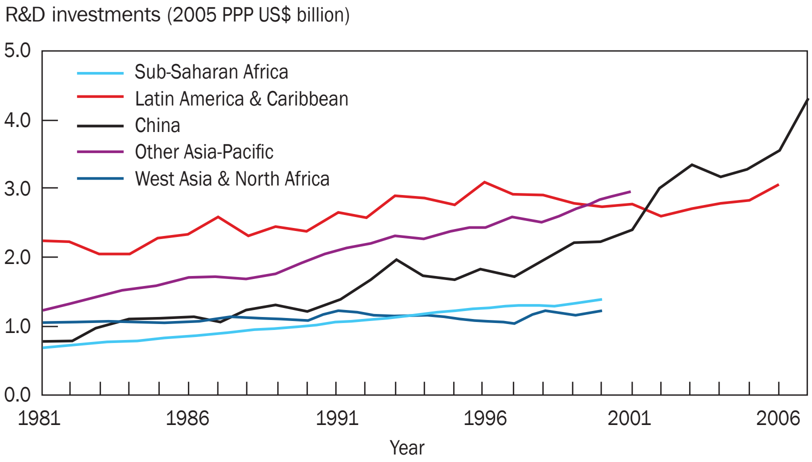

Fig. 2. Public agricultural R&D investment trends in developing countries, 1981-2006. Sources: ASTI data sets and secondary sources underlying Beintema and Stads (2008, 2010) and Stads and Beintema (2009).

The government sector is still the main player in public agricultural R&D, in terms of execution as well as funding. The government sector accounted for 60% and 77% of total full-time equivalent (FTE) staff in Latin America (data for 2006) and sub-Saharan Africa (data for 2000-01), respectively. Despite this leading role of the government sector, the higher-education sector has gained prominence in several countries, but the individual capacity of many higher-education agencies remains very small.

The government sector is also still the largest funder of public agricultural research (Echeverria and Beintema 2009). Government allocations accounted, on average, for 81% of total funding received by a sample of more than 400 government agencies in 53 developing countries. Only 7% of total funding was received from donor contributions, in the form of loans or grants. Funding generated through internally generated funds, including contractual arrangements with private and public enterprises, accounted for an average of 7% of total funding. These data do not include the increasing role of private foundations in agricultural research in recent years. The most important funder in this group is the Bill & Melinda Gates Foundation (BMGF). For example, BMGF approved roughly $450 million in agricultural development grants in 2009 focusing on sub-Saharan Africa and South Asia, including significant investments in rice research led by IRRI, AfricaRice, the Chinese Academy of Agricultural Sciences (CAAS), and their partners.

The private sector accounted for 41% of the global total, with almost all of these investments by private companies performing agricultural R&D in high-income countries. Investments by the private sector in the developing world accounted for only 2% of the total public and private agricultural R&D investments in 2000, of which most came from private companies in Asia (Beintema and Stads 2010). At the global level, the private sector now plays a leading role in conducting research in areas such as breeding of maize, soybean, vegetables, and increasingly also rice; research on new pesticide or fertilizer formulations; and equipment for agriculture and processing. Global private agricultural research spending remained fairly stagnant over the past decade, although a shift occurred from chemical to biological technology. The top 20–25 companies, in terms of market share, conduct nearly all R&D in most agriculture-related input sectors. The private agricultural input industries invested $7.3 billion in 2006, of which agricultural chemicals and crop seed and biotechnology industries each accounted for close to one-third of these total investments (preliminary results forthcoming in Fuglie et al 2010). In developing countries, limited private-sector involvement often focuses on the provision of input technologies or technical services for agricultural production and most of these technologies are produced in the high-income countries (Pardey et al 2006).

The IARCs have made an important contribution to the provision of improved agricultural technologies to developing countries, especially the technologies that ushered in the Green Revolution (Hazell, this volume). After two decades of high growth in total investments, the rate of growth slowed considerably during the 1990s. Since 2000, funding grew from $305 million in 1991 to $524 million in 2008 (Fig. 3), an increase of 70% in current prices, but, when adjusted for inflation, the increase declines to 20%. Many commodity-oriented IARCs, including IRRI, suffered from a major decline in funding as the CGIAR invested more in research on natural resources, policies, or other areas. Moreover, whereas nearly all funds during the 1980s were unrestricted and could thus be invested in long-term research programs, the trend since then has been toward support for specific projects and programs, often with shorter time frames and involving multiple centers and other research providers outside the

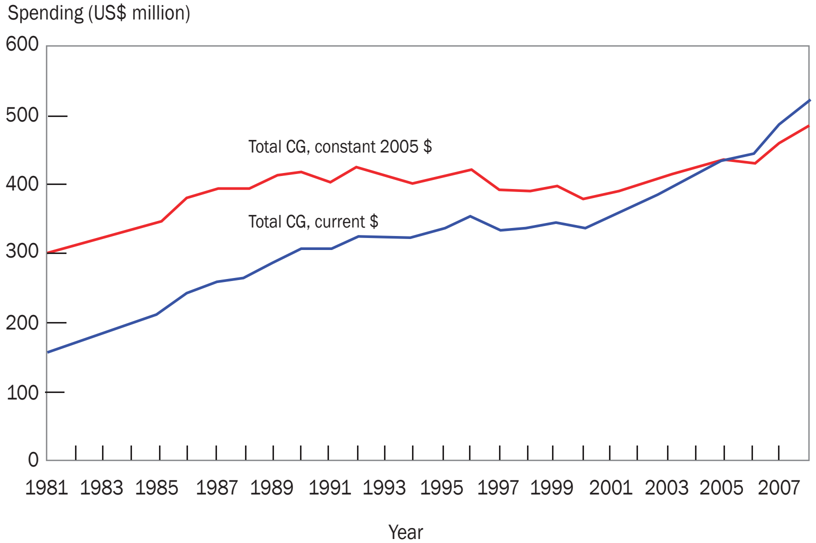

Fig. 3. Spending of the CGIAR, 1981-2008. Sources: Adapted from Pardey et al (2006) and CGIAR annual reports.

CGIAR. Current funding at IRRI and AfricaRice, for example, is 75–80% through dozens of such restricted projects. Managing research programs in a coherent manner to enable a continuous stream of innovations has thus become a lot more challenging.

The changes in the organization and investment levels in global agricultural research as outlined above are of importance to rice research and the role of the CGIAR (specifically, IRRI, AfricaRice, and CIAT). For example, the role of universities is changing in many countries, including some of the main rice-producing ones and how they will affect the various rice partnerships in place. The falling commodity research focus within the IARCs has its bearings on rice research. And, because governments are still the main performer and funder of public agricultural research, their engagement in funding national-level rice programs remains important. Furthermore, it is not only necessary to invest more in rice R&D, but the mechanisms for such investments should also be streamlined. Donors' needs for accountability and visible impact are often not well aligned with the needs of those who conduct research. For many technologies, it takes about 10–15 years until a significant impact can be attributed to a specific R&D investment. This reality often contradicts the desire to demonstrate quick impact from an investment in R&D.

Public rice research investment trends and institutional arrangements

Detailed trend data on rice research investments are not available. But, the ASTI initiative has been collecting detailed information on the research orientation of public research staff by commodity through their institutional survey rounds in close to 60 low- and middle-income countries.[4] On average, more than half of the total agricultural researchers, measured in FTEs, focused on crop research (Beintema and Elliott 2009). Of these crop researchers, an average of 10% focused their research activities on rice (Fig. 4). Unsurprisingly, a relatively higher share of the crop researchers, on average, in the Asia-Pacific region conducted rice research (15%). These regional averages mask a wide variation across countries. In Bangladesh, Lao PDR, Nepal, the Philippines, Burkina Faso, Guinea, Madagascar, Mali, and Mauritania, rice accounts for more than 20% of the total FTE researchers focusing on crops. In a number of other countries, however, the share of rice in total crops is less than 5%. In all regions, more focus is accorded to cash crops than to rice. It is also particularly striking that only 8.1% (that is, 15% of the 54% of total FTE researchers that focus on crops) of all agricultural research resources in the Asia-Pacific region focus on rice, whereas rice represented approximately 25% of the value of the top 20 agricultural commodities in the region (FAOSTAT data from the early-mid-2000s), and is the key staple for most of the region's population.

There are different ways in which rice research is funded and organized in the various countries and regions where rice plays an important role. Several Asian coun-

[4]Data results were published in Beintema and Stads (2006, 2008) and Stads and Beintema (2009). See also country snapshot tables at www.asti.cgiar.org.

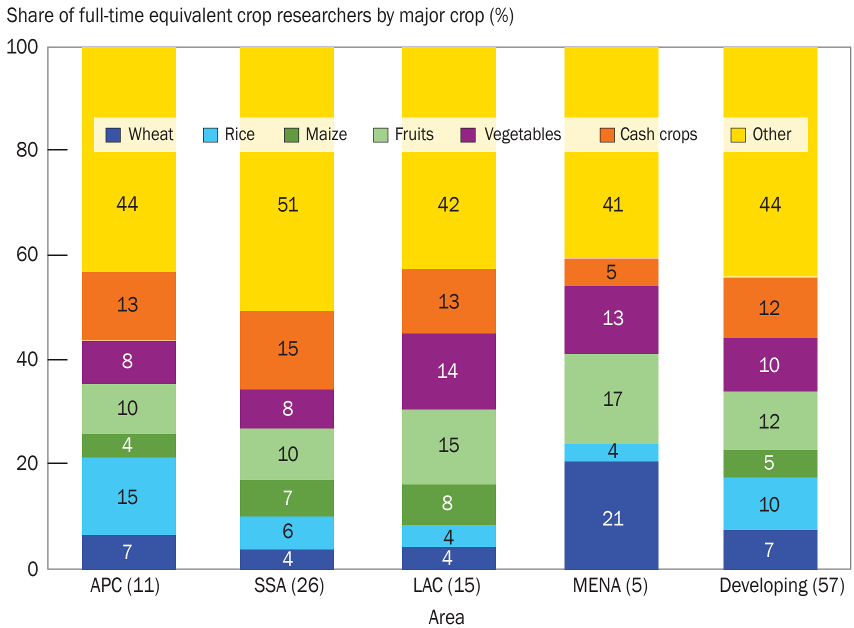

Fig. 4. Research orientation of crop research staff by main crop for the public sector, early 2000s. Source: Authors calculations based on ASTI data sets (www.asti.cgiar.org). The number of countries included in the regional totals is shown in parentheses. SSA stands for sub-Saharan Africa, APC for Asia-Pacific countries (and excludes here China), LAC for Latin America and the Caribbean, and MENA for Middle East and North Africa. SSA data are for 2000-01, APC for 2002, LAC for 2006, and MENA for 2002-03. Data exclude researchers employed by private companies. Cash crops include cocoa, coffee, cotton, oilpalm, sugarcane/beet, tea, and tobacco.

tries have strong national programs of rice research, which include specialized rice research agencies. In contrast, rice research capacity in Africa, with the exception of Egypt, is limited and is mostly conducted by AfricaRice, in close collaboration with national programs. Below follows a description of the organization, investment patterns, and concerns related to rice research in Asia, Latin America, and Africa.

Rice research in Asia

Asia has the world's largest concentration of rice research, which is conducted at government and higher-education agencies, nonprofit institutions, and nongovernment organizations; IARCs, specifically IRRI; and private for-profit companies (for the latter, see the fourth section).

In many Asian countries, a significant part of the national rice research is conducted by specialized rice research institutes such as the Philippine Rice Research Institute (PhilRice) or the Chinese National Rice Research Institute (CNRRI). Typically, these specialized institutes belong to larger bodies that have a national responsibility for agricultural research, such as the CAAS and the Indian Council on Agricultural Research (ICAR). ICAR has two large multidisciplinary institutions to conduct research on rice, the Directorate of Rice Research (DRR) for irrigated rice environments and the Central Rice Research Institute (CRRI) for rainfed environments in India. In addition, a good deal of rice research is being done in various other organizations of ICAR responsible for resource and multicommodity research.

In addition to these formal rice research institutes, universities and other government or nonprofit agencies are also engaged in rice research. The university sector is particularly strong in countries such as India, China, and Japan, but differences exist in the nature of rice research in this sector. In many countries, universities focus more on basic research and have their own projects and partnerships. In India, however, State Agricultural Universities (SAUs), modeled around the U.S. Land-Grant University system, participate actively in research, and also have state-wide responsibilities for frontline extension activities such as farm testing and transfer of new technologies. Universities in China also play a strong and even increasing role in applied research for extension purposes. Similar developments can be found in some other countries such as Nepal, Pakistan, and the Philippines.

Coordinating national rice research and extension activities across the government and the university sectors often faces difficulties. Whereas government institutes tend to operate based on medium-term and annual plans (and budgets), the more diverse university sector lacks such a central R&D planning and management approach. Duplication of research is not uncommon and potential synergies that could result from better cooperation are often not harnessed. The Indian system is an exception in that it has a mechanism of coordination of research under various public organizations and this responsibility is supported by ICAR and managed by DRR.

Exact figures of recent investments in rice R&D in Asia are difficult to obtain, also because of rapid changes during the past few years. The most recent comprehensive data from the early 2000s indicate funding that is less than congruent with the production value or food security importance of rice. However, in light of the re-emerging food security concerns in Asia, many governments have significantly increased their investments in the agricultural sector in recent years, including the rice sector and rice R&D. India, for example, has heavily invested in the National Agricultural Innovation Project and extension efforts are accelerated through the National Food Security Mission. As a result, ICAR is currently recruiting many new scientists. China has recently announced massive investments in the agricultural biotechnology sector. Indonesia and the Philippines have set ambitious targets for raising rice productivity annually at 3% or more during the coming years. In 2005, Thailand created a Rice Department under the Ministry of Agriculture and Cooperatives, which deals with all aspects of the Thai rice sector, including R&D.

Although some nongovernment organizations play a significant role in rice research, their overall proportion of the total R&D output remains quite small. Well-known examples include the Energy Research Institute (TERI) and the M.S. Swaminathan Research Foundation in India. More partnerships of civil society organizations (CSO) with the research sector have been emerging in recent years. Facilitating this is also an increasing role of IARCs and other international organizations in the region through national projects or regional networks and consortia.

IRRI continues to make major contributions to global rice research, and, despite stronger national rice research agencies in, for example, India and China, it continues to play a leading role in Asia. But, as mentioned earlier, IRRI suffered from a major decline in funding from the early 1990s onward, which was particularly large for unrestricted funding (from 70% of total funding in 1990 to 21% in 2009). Because unrestricted funding is needed to fund long-term programs, staffing, and infrastructure, IRRI had to curtail many of its long-term research and capacity-building programs, particularly in rice breeding. IRRI's total staff decreased from a high of nearly 3,000 in the late 1980s to less than 1,000 by 2007.

In recent years, however, IRRI's annual budget has nearly doubled, from close to $30 million in 2006 to about $54 million in 2009, which was the result of three major factors. First, IRRI's new strategic plan for 2007-15 (IRRI 2006) represented a significant change from previous priorities. More emphasis is now placed on marginal rainfed environments, diversification of rice systems, the sustainability and environmental consequences of intensive rice production, and genetic discovery research. New programs were started on improving human health through biofortified rice and rice in eastern and southern Africa. Second, the increased focus on a more product-oriented R&D approach resulted in stronger donor support, particularly by new donors. In 2009, BMGF accounted for about one-third of the annual budgets of IRRI and AfricaRice. Many of these grants initially focus on short- to medium-term impacts (products already in the pipeline), but also provide support for basic research such as on C_4 photosynthesis in rice.

Rice research in Latin America

Similar to Asia, rice research is conducted by a combination of public, private, and international agencies. Rice research in Brazil, Costa Rica, and Colombia, for example, is done by the main government research agency as well as by producer organizations or through other nonprofit institutional arrangements. Brazil (with substantial resources for upland R&D) and Uruguay (irrigated rice) have had the most stable and successful public rice research in the region, but other countries have had unstable public rice R&D funding. In addition to national efforts, CGIAR research has been vital for sustaining the productivity and profitability of the rice sector in this region, and this mandate is fulfilled by CIAT, created in 1967.

By the end of 1993, however, CIAT's financial resources for its rice program started to decline sharply, from $4 million in 1990 (mostly core) to just over $1 million in 2008 (mainly restricted). This caused alarm due to the high dependence of the Latin American rice sector on CIAT to sustain innovations, particularly in germplasm research. Fostered by CIAT, an initiative was set up to create a self-relying research effort based on financial contributions by the private sector, which led to the creation of the Latin American Fund for Irrigated Rice (FLAR) in 1995. By 2009, FLAR received financial contributions of about $1 million a year from 15 member countries and CIAT.[5] External assistance to FLAR from the international donor community enabled the organization to expand its research agenda beyond the initial focus on germplasm development. This includes, for example, projects on bridging yield gaps and water harvesting in Central America and a project on varietal cold tolerance. FLAR has also created a fund from the sale of seed from new varieties released by partners from FLAR germplasm to support CIAT´s rice-related activities.

Close to 300 rice varieties were released by 23 national programs from 1967 to 2000. More than 40% of the released varieties were crossed at CIAT (CIAT 2004). Rice farmers have also benefited from research done at IRRI (at least 13 IRRI-developed rice varieties were released in the region). High-quality downstream research activities (through locally relevant adaptive efforts) at the country level, frequently involving cooperation between government agencies and private producer organizations, were key to expanding the spread of improved germplasm, complementary cultural practices, and related institutional and policy developments. The majority of the new varieties released (90%) were targeted to flooded environments. Rice in Latin America evolved, during the 20th century, from a pioneer crop for upland environments to an irrigated crop.

Latin America has made important progress in finding stable resources for rice research. In addition to the creation of FLAR, national associations generate funding through various means such as production check-offs, sale of germplasm, royalties, and the commercialization of inputs and products. Government research agencies and producer associations allocate significant resources to their own R&D rice agendas. CIAT continues to play a major role as a neutral, credible, and reliable convener of FLAR and as a leading regional research center, focusing on upstream rice research issues.

The main future challenges for Latin American rice R&D are to (1) stabilize funds for international projects in the region for CIAT and FLAR at around $6–7 million per year; (2) strengthen collaboration between IARCs and the traditional main rice R&D agencies, such as Embrapa of Brazil, Center for International Cooperation in Development-oriented Agricultural Research (CIRAD) and IRD of France, and FLAR, emphasizing the need to maintain open interchange and easy access to farmers; (3) build new internal linkages across private, public, and civil society organizations to improve mechanisms to reach the end-users of research, with the added task of enhancing the roles of universities in the system; and (4) expand collaboration with other R&D institutions outside the region.

Rice research in Africa

In contrast to Asia and Latin America, Africa's national capacity in rice research has been very limited and mainly at national research institutes, universities, and IARCs. Realizing the seriousness of the capacity constraints in African rice research, the West Africa Rice Development Association (WARDA) was established by 11 African countries in 1971. WARDA joined the CGIAR in 1986 and was renamed the Africa

[5]These countries represent about two-thirds of the rice production in Latin America.

Rice Center (AfricaRice) in September 2009. As of 2009, 23 countries[6] had joined AfricaRice. A survey conducted among AfricaRice's member states in 2008 showed that approximately 250 to 275 researchers (about 15 women) are involved to some extent in rice research. Most of them work on many other crops and spend only a fraction of their time on rice. Egypt alone takes the lion's share of this research pool with 50 highly qualified researchers working full-time on rice, including 12 rice breeders. In comparison, a country the size of Nigeria has only two rice breeders.

Given the extremely low capacity in rice research in Africa, it is essential to bundle efforts. AfricaRice has convened two rice research networks, one in West and Central Africa (ROCARIZ), involving 17 countries, and one in East and Central Africa (ECARRN), involving 10 countries. An Africa-wide Rice Breeding Task Force has been established with major support from the government of Japan.

Despite this tremendous shortage in human capacity, more than 200 rice varieties developed by AfricaRice and national and international partners have been released in sub-Saharan Africa over the last 20 years. These include interspecific varieties of NERICA (New Rice for Africa), along with *Oryza sativa* varieties (the successful Sahel series for Sahelian irrigated conditions). Most of these varieties were tested through AfricaRice's previous four rice breeding task forces focusing on upland, rainfed lowland, irrigated, and mangrove rice ecologies. Breeding lines from IRRI, such as IR64 (a progenitor of the modern NERICA varieties), have been used to develop locally adapted African rice varieties. Gene discovery work conducted with universities based in France, Japan, and the U.S. has identified genes responsible for resistance to major rice diseases in Africa.

AfricaRice and national partners have also developed integrated rice management (IRM) options for the main rice ecologies through farmer participatory research, detailed physiological studies, and crop modeling. Small-scale mechanization will be essential to realize gains in rice production in Africa. South-south knowledge exchange will be crucial in this respect. AfricaRice imported an axial-flow thresher-cleaner from IRRI (originally from Vietnam) in the late 1990s and tested and adapted the machine to African rice-cropping conditions with local artisans and partners in Senegal. This thresher-cleaner is now manufactured locally and is widely available in Senegal, Mauritania, and Mali.

In a number of countries, initiatives to boost the national rice sector are coordinated at the ministerial or presidential level (e.g., Mali, Senegal, and Nigeria). The Africa Rice Initiative, hosted by AfricaRice, operates in seven countries in West Africa and has been mainly focusing on providing farmers with better access to quality rice seed of improved varieties. Also in 2008, the Japan International Cooperation Agency (JICA) in collaboration with the Alliance for a Green Revolution in Africa (AGRA) launched a Coalition for African Rice Development (CARD) to double rice production

[6]Benin, Burkina Faso, Cameroon, Central African Republic, Chad, Democratic Republic of Congo, Republic of Congo, Côte d'Ivoire, Egypt, Gabon, The Gambia, Ghana, Guinea, Guinea Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Togo, and Uganda. Madagascar was expected to join in 2010.

in sub-Saharan Africa in 10 years compared with 2008 levels. CARD is a facilitating body building on existing policies and programs, such as the Comprehensive Africa Agriculture Development Program (CAADP) and Africa Rice Initiative. A recent study by AfricaRice and IRRI estimated that, for the first group of 12 CARD countries, at least 900 rice researchers and 1,000 trained technicians (using a ratio of two technicians per researcher) would be required to reach the CARD goal of doubling rice production in 2018. For a country the size of Nigeria, at least 88 researchers would be needed by 2018, including 30 breeders.

In recent years, AfricaRice and IRRI have joined forces to accelerate rice R&D efforts in Africa. AfricaRice has embarked on a new strategy and greatly enhanced its research activities and funding in recent years. AfricaRice's budget doubled from 2007 to 2009 to a total of $20 million, mainly as a result of increased support from member countries, Japan, USAID, and BMGF. In 2006, IRRI made the strategic decision to create a special research program for rice in eastern and southern Africa, with a base in Maputo, Mozambique. In 2008, AfricaRice and IRRI developed a joint eastern and southern Africa Rice Program, which is now being implemented through a joint AfricaRice–IRRI office in Dar Es Salaam, Tanzania. By the end of 2009, about 25 research staff were employed by both institutions in eastern and southern Africa, up from only four in 2007.

The role of the private sector in rice research: recent developments in Asia[7]

Breeding of improved rice varieties worldwide has been dominated by the public sector, while the private sector mostly focused on developing pesticides, fertilizers, and machinery for rice cultivation. Unfortunately, no data are available on the absolute or relative size of the investments of the private sector in rice R&D. The limited role of private R&D in rice breeding has been primarily due to the fact that companies could not easily appropriate part of the gains in yield and quality that farmers obtain from improved varieties. Rice is a naturally self-pollinated plant and so it is easy for farmers or seed companies to reproduce any new variety. In recent years, the ability of private firms to appropriate gains from rice R&D has increased, which has induced companies to start investing in rice breeding. In addition to the advances in hybrid rice, a second important development is the ability to develop and patent biotechnology innovations.

Hybrid rice

The first rice hybrids were released to Chinese farmers in 1974 and, with substantial government support, quickly spread among farmers and, in 2007, covered almost 16 million ha, 55% of China's rice area (Pandey and Bhandari 2010). Following the Chinese success, governments and companies in many countries have made major

[7]This section focuses on the private for-profit sector. Nonprofit private agencies such as cooperatives and producer organizations are defined under public agricultural R&D and discussed in the third section (see also footnote 2).

efforts to commercialize hybrid rice, but its adoption outside China has remained slow for many years. It has been rising faster in recent years, particularly in India and Bangladesh, but also in the U.S. and in Brazil.[8] Many large multinational as well as national companies are now engaged in rice seed production and the development of hybrids.

Estimates of the global diffusion of hybrid rice remain somewhat uncertain, but it appears that hybrid rice is now grown on about 20 million ha of the world's rice land (about 13%). The major R&D investments made in recent years by the private sector will likely lead to significant technological progress and a more rapid increase in hybrid rice area outside of China. A key consequence of these developments is that the public-sector R&D system needs to re-define its role in hybrid rice development, focusing on public-private partnerships in which the public sector acts more as a pre-breeding and general research provider rather than trying to commercialize hybrids itself.

Indeed, the public sector has been the backbone of private efforts to date. IRRI has been a major source of restorer lines for the Chinese hybrid rice programs and revived its own hybrid rice breeding program in 1979. Through the efforts of IRRI, public research institutes in India, Vietnam, Indonesia, and the Philippines established their own hybrid rice programs in the 1990s, which led to the release of a first generation of public-sector hybrids (mostly from IRRI or with IRRI parents). In addition, there are also the first cases in which private companies have licensed rice hybrids bred by the Southeast Asian public R&D sector. DuPont, for example, has recently licensed hybrids and breeding lines from the Indonesian Centre for Rice Research. The chapter "Rice seed provision and the evolution of seed markets" (Tripp et al, this volume) provides a good discussion of the roles of the public and private sector in the development of rice hybrids and the production of hybrid seeds.

Biotechnology

A second factor leading to increased private-sector interest in rice breeding is the ability to develop and patent biotechnology inventions (see Tripp et al, this volume, for additional discussion on this). In the 1990s, Monsanto and Syngenta invested substantial amounts of money in mapping the rice genome, which was partially contracted out to universities, built on research networks financed by the Rockefeller Foundation and the Japanese government. The main interest of the private sector in the rice genome was its potential application to other crops such as maize.

[8]After an earlier failed attempt, hybrid rice was pioneered in the U.S. by RiceTec, Inc., which also acquired germplasm and technical assistance from China. Since its establishment in 1989, RiceTec has been working on developing commercial hybrids for the U.S. and Latin America, specifically in Brazil. By 2009, RiceTec hybrids were sown on at least 184,000 ha, or 15%, of the U.S. rice area (U.S. Rice Federation 2009). This estimate of hybrid seed area is based on information available from three states—Arkansas, Louisiana, and Mississippi, which together account for about 70% of the U.S. rice area. The nationwide area under rice hybrids is likely to be somewhat larger.

The potential for future earnings from transgenic traits in rice has attracted most of the major agricultural seed-biotechnology firms to invest in rice biotechnology research both in-house and through collaboration with public institutes. DuPont/Pioneer, Bayer, Syngenta, and BASF have in-house basic biotechnology programs that include rice and have located biotechnology research facilities in the United States, Europe, India, Singapore, and China. Some of these companies have partnerships with small biotechnology firms to develop yield traits for rice. These companies also engage in collaborative biotechnology rice research with the public sector in many countries, most extensively in China, and with IRRI (see the next section).

The future roles of public- and private-sector R&D investments in biotechnology depend largely on access to advanced technologies, proprietary information, regulatory costs for transgenic events, and the ability to implement excellent product stewardship. In some cases, public-sector institutions will be able to use proprietary biotechnology developed in the private sector, for example, through a free licensing mechanism that restricts usage for nonprofit purposes to certain world regions (developing countries). Golden Rice, enriched with provitamin A, is one example for this model, in which the public sector has been granted a license for such humanitarian purposes. However, any decision to undertake research activities leading to the development of a transgenic rice product entails a considerable financial commitment over a long period of time, due to lengthy and uncertain regulatory procedures for approval. It is therefore foreseeable that the development and commercialization of transgenic traits will remain largely in the hands of a relatively few companies.

Public-private partnerships

The expansion of the rice seed sector is leading to an increased diversification of rice R&D systems through formal research partnerships and contractual relationships among the public and private sector. They aim at using the comparative advantages of both sectors for accelerating R&D and product delivery to rice farmers and others in the value chain. Many of them are in the seed sector, but there are also examples for other technologies. We concentrate here on providing a few recent examples from Asia, mainly to illustrate various models.

With initial support from the Barwale Foundation, ICAR managed a public research network for developing hybrid rice, which used many IRRI materials and resulted in a first generation of rice hybrids in India. To support the nonexclusive commercialization of these hybrids, the Barwale Foundation established the Indian Foundation Seed and Services Association (IFSSA), with a mandate to enhance the supply of source seed and make it available to public and private seed agencies. This is done through a nonexclusive, royalty-bearing agreement. For example, IFSSA entered into an agreement with the Indian Agricultural Research Institute (IARI, New Delhi) for commercializing the first basmati rice hybrid (Pusa RH-10) developed by IARI. IFSSA undertook the maintenance breeding and nucleus, breeder, and foundation seed multiplication of Pusa RH-10 for more than 40 member seed companies. The royalty revenue generated is used to support IARI's additional research and to recover IFSSA's operational costs. The same approach is now being followed for other rice hybrids developed in the public sector and this model may also be expanded to inbreds and other crops in the future. IRRI also plans to market its hybrids in India through the IFSSA mechanism. The key feature of this model is that it is self-sustaining and it provides nonexclusive access to high-quality seed of public-sector hybrids to numerous smaller seed companies.

IRRI has pioneered several public-private partnership models, some dating back to the late 1990s, and currently has agreements with more than 40 private companies. IRRI ensures that all its private-sector partnerships support IRRI's mission and strategic plan, provide equal opportunities to any potential private-sector partner, avoid complex intellectual property (IP) issues, are nonexclusive, follow the International Treaty on Plant Genetic Resources for Food and Agriculture, and avoid promotion of private-sector products. Two major models of relationships with the private sector are described below.

Private companies or industry associations may make contributions to specific research areas or to international consortia that involve a large number of public- and private-sector partners. For example, since 1997, three international fertilizer industry associations have provided additional support to the Irrigated Rice Research Consortium (IRRC), which receives its main funding from several public-sector donors. These funds were used by IRRI and its national partners to conduct research on new approaches for efficient, sustainable nutrient management in rice-based systems. Another example is the Hybrid Rice Development Consortium (HRDC), with 25 seed companies as well as 25 public-sector institutions as its members (as of May 2010). These include large multinational companies such as Bayer, Syngenta, and DuPont, but also numerous other companies from India, China, Bangladesh, Indonesia, Pakistan, Malaysia, Belgium, Bolivia, and the United States. Private-sector members pay annual membership fees. Additional income is generated from development fees for prebreeding lines and nonexclusive, royalty-bearing licensing of pilot hybrids to private companies. The latter may also include joint licensing with other research partners from national systems, if the latter have been involved in the breeding effort. The income generated is used to support hybrid-related research by IRRI and its partners.

The private sector also has specific expertise and networks for delivering products and services effectively and efficiently to farmers. By working with private-sector partners on a nonexclusive basis, another channel for delivering public research solutions is enabled. In such cases, IRRI provides initial technical support and assistance with capacity building for delivering new technologies coming out of research conducted by IRRI and its national partners. Private companies, like other partners, use their own resources to deliver these technologies to farmers and also provide feedback for further improvement. In networks and large technology transfer projects, IRRI often facilitates this interaction on the ground, involving public-sector companies as well as NGOs. One is with Syngenta in Bangladesh, where the company, through its own network of agronomists and dealers, promotes the use of alternate wetting and drying—a crop management method that can improve water-use efficiency in rice.

Measuring underinvestment in public rice research: the case of Southeast Asia

Substantial resources are currently invested in rice research, but are these sufficient or is rice research under- or overrepresented in agricultural research portfolios? This section attempts to answer this question in the context of Southeast Asia. This subregion was chosen because of its relatively rapid economic growth, rice-dominated diets, and the world's highest per capita rice production and consumption. It might, therefore, be expected that rice receive adequate attention in public agricultural research agencies.

Southeast Asia is also an interesting focus because it is claimed that it has moved into economic transition, in which staple food self-sufficiency goals should now be trumped by a focus on higher-value commodities, as a result of growing levels of wealth (e.g., Timmer 2009), implying a concomitant shift in research resource allocation. This section therefore attempts to tackle the poverty relevance of continued rice research in the midst of economic growth, using Southeast Asia as a bellwether.

In Southeast Asia, rice comprises less than 10% of public agricultural research staff, as crop research is slightly less than half of known public-sector expenditures, and rice is just over one-fifth of crop research.[9] For the IARCs, rice is 22% of known subregional expenditures.[10] To begin to assess how these resource allocations compare with impact potential, 2007 data on the value of production of different agricultural commodities have been assembled from FAOSTAT and the U.S. Department of Agriculture, and adjusted to 2020 based on extrapolation of historical trends in production.

Standard economic surplus equations, in conjunction with forecasted values of production, are applied to forecast the expected economic benefits of alternative research investments using an assumed productivity shift of 5%. These equations are differentiated for domestically consumed commodities, exported commodities, and imported commodities. Details of the assessment approach are presented in Raitzer et al (2009).

In terms of estimated expected benefits, productivity improvement of rice yields the greatest benefits, at $2.1 billion of economic benefits per year (Table 1). Note that, for most domestically consumed crops, a greater percentage of the benefits of productivity enhancement goes to consumers than to producers.

The ability of the poor to benefit from this producer surplus depends upon the value of their production that can benefit from new technologies, as well as whether they are producing and marketing the crop directly or acting merely as contract labor. The value of production by the poor has been estimated using a raster grid spatial data set on headcount prevalence of poverty at the state and municipal levels (Monfreda et al 2008). Using these data, the poverty relevance of major agricultural crops is

[9] Based on analysis of ASTI data, which are available on the ASTI Web site (www.asti.cgiar.org).

[10] Based on Asian expenditures reported in CGIAR Financial Reports and adjusted to reflect Southeast Asia.

Table 1. Annual economic benefits in Southeast Asia of a 5% improvement in productivity, based on projected values of production in 2020 and adjustments to reflect the proportion of production by those earning less than PPP US$1/day.[a]

Commodity	Aggregate surplus (PPP US$, million)	Consumer surplus (PPP US$, million)	Producer surplus (PPP US$, million)	Percentage of benefits to poor producers	Percentage of benefits for top commodities
Rice	2,082	1,541	541	62	42.6
Palm oil	1,309	348	961	35	23.6
Aquaculture	710	474	237	n.d.	n.d.
Pork	515	322	193	n.d.	n.d.
Poultry	466	311	155	n.d.	n.d.
Vegetables	441	315	126	15	10.6
Cassava	304	190	114	13	8.9
Fruit	325	232	93	10	7.1
Coconuts	224	140	84	10.	6.9
Eggs	208	139	69	n.d.	n.d
Sugar	175	109	66	8	5.3
Bananas	168	99	70	8	5.7
Beef	152	102	51	n.d.	n.d.
Coffee	102	21	80	6	3.9
Maize	93	0	93	12	8.0
Groundnuts	85	57	28	4	2.4
Pepper	74	18	56	n.d.	n.d.

[a]All values are based on 2007 prices, and are expressed in millions of PPP-adjusted US$.
Source: Raitzer et al (2009); note that poverty adjustments are based on proportions of poor in areas of crop cultivation, do not take into account differences between contract and family farm cultivation, and omit livestock. n.d. indicates no data.

compared through a multiplication of the amount of production in a specific grid cell by the proportion of the population living on less than $1 per day in a given location. This gives an approximation of the proportion of production of different crops by the poor. Rice has a dominant proportion of benefits to poor producers, as nearly half of the benefits accrue via this crop. Vegetables, cassava, maize, fruit, and coconuts follow at much lower levels (Table 1). Note that these numbers are conservative, as many of the poor in Southeast Asia now fall in the $1–2 per day poverty range, and are hence excluded from these estimates. In addition, benefits to poor producers who consume their own production are omitted, as are the benefits of maintained market share.

For consumers, benefits are primarily manifested through lower prices. The degree to which this benefits the poor depends upon the share of the poor population's income expended on the agricultural product. In terms of expenditure by the poor, rice is clearly by far the commodity on which the poor spend the most (Table 2). Nearly one-quarter of household expenditure for those under the $1.25[11] per day poverty line is for rice. The next highest area of expenditure, vegetables, is more than three times lower, followed by fish at nearly the same level.

The poverty alleviation effect for consumers of research-induced productivity enhancement can also be calculated using future adjusted expenditure data, along with headcount measures of poverty, the poverty gap, and price effects, as described in Raitzer et al (2009). This yields the results in Table 2. It is clear here that rice dominates expected benefits in the same manner that it dominates expenditures of the poor, even when future dietary changes are taken into account.

A caveat to this analysis is the assumption of equal probability of success in fostering improved productivity across different focal commodities through successful technologies and their widespread adoption. Indeed, documented patterns to date reveal substantial heterogeneity in research impact achieved across agricultural products. However, the greatest productivity improvements observed in the subregion to be attributable to research so far have been in rice (Raitzer et al 2009). In terms of overall

Table 2. Annual benefits to Southeast Asian consumers with incomes below a PPP US$1.25 per day poverty line from a 5% average improvement in productivity for specific agricultural products, considering reduced food expenditure as income, and adjusted for expected changes to dietary composition in 2020.

Commodities	2005 expenditure share for those earning less than PPP US$1.25/day (%)	No. of people lifted above the poverty line (million)	Annual benefits to the poor (PPP US$ million)	Share of benefits to the poor from top 11 foods (%)
Rice	24.0	8.1	316.0	43.7
Vegetables	7.9	3.7	143.1	19.8
Fruit	3.7	1.5	59.3	8.2
Aquaculture	7.6[a]	1.2	44.7	6.2
Poultry	1.5	0.8	30.4	4.2
Sugar	1.9	0.8	30.2	4.2
Pork	1.8	0.7	27.1	3.8
Palm oil	2.3[b]	0.7	26.7	3.7
Eggs	1.4	0.5	20.7	2.9
Beef	0.3	0.1	4.4	0.6
Lamb, goat	0.1	0	0.7	0.1

[a]Expenditure on aquaculture includes all fish and seafood. [b]Expenditure on palm oil includes all oils and fats.
Source: Raitzer et al (2009).

[11]The use of a US$1.25 per day poverty line, rather than $1 per day, was dictated by data availability.

yield effects attributed to research, rice, wheat, and maize far surpass any other crops (Evenson and Rosegrant 2003). Yet, the agricultural research intensity ratios (ARIs, proportions of investment in research relative to proportions of value of agricultural gross domestic product) for rice are far lower than for other crops, as rice represents 26% of the aggregate projected 2020 production value of major commodities, but less than 10% of national agricultural research and extension systems (NARES) expenditures, and represents a three times larger share of AgGDP (agricultural gross domestic product). The rice ARI is far below other more minor commodities, such as bananas or beef, which do not have similar patterns of documented research-induced productivity growth. This suggests that the ARI required for a unit productivity improvement in rice is probably lower than for other commodities, and reinforces the case for underinvestment.

Although this analysis is largely driven by value of production, it also makes distributional distinctions based on market characteristics and poverty relevance. As a result, rice is found to represent a higher proportion of expected benefits to poor consumers (44%) and producers (43%) than its projected proportion of production value (26%). The share of potential economic benefits is approximately three times the share of public research budgets allocated to rice, whereas the proportions of assessed benefits to poor consumers and poor producers are four times the share of current NARES expenditures on rice (Table 3). For international agricultural research, the disparity is less overt, but relative underinvestment is also apparent.

Broader evidence of underinvestment

This analysis accords with substantial documented evidence of high benefit levels from investment in rice research, particularly in rice genetic improvement. For example, in inflation-adjusted terms, the aggregate of estimates from Sanint and Wood (1998) and Hossain et al (2003) is $19.5 billion of annual benefits from improved rice varieties in Asia and Latin America. According to Alston et al (2000), the median reported rate of return to rice research is 51.3%, higher than any other specific crop. Such returns are indicative of underinvestment in an area with demonstrated impact potential. Although many of these studies do not use an explicit economic surplus framework to partition benefits between consumers and producers, those that do, such as the ex ante assessment presented in the previous section, find that a majority of benefits accrue to consumers. Given that rice has a low to negative income elasticity in most developing countries (so that per capita consumption is as high among the poor as among the rich), and comprises a high proportion of household expenditures by many poor people, such benefits to consumers through reductions in rice prices are rather pro-poor (see the next section). Accordingly, Ivanic and Martin (2010) find that productivity-enhancing research on rice has more potential to reduce poverty than productivity-enhancing research on any other commodity. Their analysis finds that a sustained 1% rate of productivity growth has the potential to reduce poverty by more than 2% in a 40-year time frame, equivalent to raising 28 million people above the $1.25 per day poverty line. Clearly, rice research is an essential element of an effective approach to global poverty alleviation.

Table 3. Comparison of expected research benefits from a 5% unit cost reduction and current allocations to different agricultural commodities.

Research focus	Potential impacts			Current investments	
	Share of overall economic benefits (%)	Share of benefits to poor producers (%)	Share of benefits to poor consumers (%)	Share of NARES FTEs (%)	Share of IARC budgets (%)
Rice	28.0	42.60	43.70	9.9	21.8
Palm oil	17.6	23.6	3.7	3.4	0
Aquaculture	9.6	n.d.[a]	6.2	3.0	7.9
Pork	6.9	n.d.	3.8	1.0	6.2
Poultry	6.3	n.d.	4.2	2.3	–
Vegetables	5.9	10.6	19.8	4.4	4.0
Cassava	4.1	8.9	0.0	0.6	1.7
Fruit	4.4	8.0	8.2	3.9	0.5
Coconuts	3.0	7.1	0	1.5	0.5
Eggs	2.8	n.d.	2.9	n.d.	0
Sugar	2.4	6.9	4.2	1.5	0
Bananas	2.3	5.6	0	3.8	1.0
Beef	2.0	n.d.	0.6	3.4	0
Coffee	1.4	5.3	0	0.6	0
Maize	1.3	3.8	0	3.7	2.8
Groundnuts	1.1	2.4	0	n.d.	0
Pepper	1.0	n.d.	0	n.d.	0

[a]n.d.=no data.
Source: Raitzer et al (2009).

Future directions in rice research

Future investment needs and challenges

Global agricultural research systems have several emerging challenges to address, such as climate change adaptation, increasing weather variability, water scarcity, and rising price volatility. These will generally increase the need for more agricultural R&D investments. Many countries will need to develop their human and institutional capacity to tackle the broadening agenda of agricultural research. In addition, countries will need a more effective financing of agricultural research. There is an increasing emphasis on creating new structures and mechanisms for collaboration within countries as well as across countries and regions. These general issues all apply for rice research as well, as outlined in this chapter.

An increasing amount has been invested in recent years in developing productivity-enhancing and/or risk-reducing technologies for rainfed rice ecologies to engineer a long-overdue Green Revolution in the poorest rice-farming regions. Recent breakthroughs in breeding new stress-tolerant rice varieties open the door for this, but this must also be accompanied by research and extension efforts on good agronomic practices in those rainfed lowland areas that are likely to benefit most from the new seeds. Tolerance of abiotic stresses, particularly drought, heat, submergence, and salinity, will continue to be a major focus area for molecular breeding work. Advances in marker-assisted breeding may also limit the need for transgenic approaches, which still confront uncertain performance and regulatory issues. Investments in transgenic solutions will, however, be required for rice traits with limited genetic diversity.

Despite progress expected to be made in rainfed areas, intensively managed irrigated rice systems will continue to supply 75% of the world's rice. Although yield gaps have become smaller in recent decades, substantial yield increases of 1–3 t/ha are still attainable in most irrigated regions. On the one hand, more needs to be invested in germplasm improvement, particularly with regard to resistance to biotic stresses, adaptation to water-saving irrigation and various forms of conservation agriculture, and improving grain quality for local markets. On the other hand, substantial productivity and efficiency gains are possible through investing in an agronomic revolution that focuses on optimizing crop and input management, resulting also in increased use efficiencies of critical resources such as water, soil, labor, and fertilizer. On-farm studies conducted in Asia in the late 1990s have shown, for example, that by improving fertilizer management alone yields could be increased by an average of about 10%, along with large increases in nitrogen-use efficiency (by 30–40%) and net profit (Dobermann et al 2002). Likewise, in southern Brazil, rice yield growth over an area of 1 million ha of irrigated rice has averaged about 0.2 t/ha per year during the past five years, which was largely accomplished through a widespread optimization of agronomic management practices on thousands of large farms. Unfortunately, investments in better agronomy, along with the necessary strong extension programs, have been grossly undervalued by many governments as well as international donors. A possible reason for this is that it has not been easy in the past to quantify the impact from such investments.

Increased investments are needed to revitalize R&D efforts on raising the yield potential of rice and more systematic inclusion of grain quality into rice breeding for specific target markets. Hybrid rice has made some progress in this regard but its spread has been rather limited. But, given recent developments, it seems likely that proprietary rice hybrids and GM varieties will see significantly wider diffusion in the coming decade, especially in Asia. An ambitious program on breeding C_4 rice with up to 50% higher yield potential started recently. It will require far larger investments than at present—sustained over 20 years. However, no other technology would offer a comparable breakthrough potential.

A greater involvement of the private sector in rice research will increase total (public and private) resources for rice improvement and raise productivity growth. Although public-sector rice breeding and biotechnology research probably still have far more resources, private-sector rice research has grown very rapidly from a small base in the last two decades. But, there is still a need for larger long-term commitments by the private sector to support public-sector research on grand challenges and international public goods, with high aggregate potential benefits, but with high risk and without an immediate commercial potential. That includes basic research, for example, on engineering of advanced photosynthesis mechanisms into rice, biological N_2 fixation in rice, insect-virus interactions, or sustainability indicators for key ecosystem services.

Whereas Africa still has a general science capacity shortage, many countries in Asia face a generation gap in rice science. IRRI's resources for providing financial and research support for educating highly qualified, well-rounded rice scientists for the public and private sector in Asia have declined steadily since the mid-1990s. This has led to a serious shortage of qualified rice scientists. A generation gap is already emerging in many public-sector institutions. Private companies have difficulties finding suitable research staff. Major shortages of scientists exist in traditional disciplines such as rice breeding, plant pathology, entomology, crop physiology, and agronomy. Capacity building, for both rice science and extension, will require sustained, joint investments by the public and private sector.

Toward a Global Rice Science Partnership

A fundamental challenge for future international rice research is to re-focus it on those strategic areas in which the IARCs can play a leading role, but ensure strong linkages with research activities by the public sector, CSOs, and the private sector. IARCs will play an increasing role as scientific leaders as well as facilitators of partnerships. A harmonized global rice R&D strategy with sustained funding will be required for addressing large breakthrough opportunities, creating synergisms instead of duplication or competition, and thus achieving greater impact faster.

Recognizing the challenges ahead, discussions on aligning the rice research agendas of three IARCs (IRRI, AfricaRice, and CIAT) began in late 2006. Over time, this has evolved toward forming a new Global Rice Science Partnership (GRiSP) under the new CGIAR Consortium, providing, for the first time, a single strategy and work plan for international rice research.

GRiSP now incorporates the rice R&D portfolios of IRRI, AfricaRice, and CIAT, as well as major parts of those of CIRAD, IRD, and JIRCAS. Together with more than 900 research and development partners worldwide, these agencies aim to implement an efficient global rice research program that follows an outcome-driven innovation approach. The partnership is also an umbrella mechanism that will allow strong national research systems that increasingly contribute to the international level to participate.

Clearly, increased investment intensity and efficiency are needed for rice research. It is expected that, through the new GRiSP mechanism, investments in international rice research will rise at rates of at least 10% per year, and these funds will be used in a more strategic, efficient manner, focusing on areas of high priority and comparative advantage, and linking public-sector research well with other, much larger investments made in national research and extension systems, grass-roots-level delivery, and the private sector. However, equally important will be that governments in developing and transition countries be willing to make similar commitments at the national level as well as increasingly contribute to supporting and thus also co-owning international rice research.

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Notes

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Acronyms and abbreviations

ACDI-VOCA	Agricultural Cooperative Development International and Volunteers in Overseas Cooperative Assistance
ADB	Asian Development Bank
AfricaRice	Africa Rice Center
AgGDP	agricultural gross domestic product
AGRA	Alliance for a Green Revolution in Africa
AgToT	Agricultural Terms of Trade
ASTI	Agricultural Science and Technology Indicators
AWD	alternate wetting and drying
BADC	Bangladesh Agricultural Development Corporation
BMGF	Bill & Melinda Gates Foundation
BRAC	Bangladesh Rural Advancement Committee
CAADP	Comprehensive Africa Agriculture Development Program
CAAS	Chinese Academy of Agricultural Sciences
CARD	Coalition for African Rice Development
CGIAR	Consultative Group on International Agricultural Research
CIAT	International Center for Tropical Agriculture
CIMMYT	International Maize and Wheat Improvement Center
CIRAD	Center for International Cooperation in Development
CNRRI	Chinese National Rice Research Institute
CPI	Consumer Price Index
CRRI	Central Rice Research Institute
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSO	civil society organization
CV	coefficient of variation
DAI	distortions to agricultural incentives
DRR	Directorate of Rice Research
ENSO	El Niño Southern Oscillation
FAO	Food and Agriculture Organization
FAPRI	Food and Agricultural Policy Research Institute
FLAR	Latin American Fund for Irrigated Rice
FPA	Fertilizer and Pesticide Authority
FTE	full-time equivalent
GDP	gross domestic product
GM	genetically modified
GMO	genetically modified organism
GMS	Greater Mekong Subregion
GR	Green Revolution
GRiSP	Global Rice Science Partnership
HRDC	Hybrid Rice Development Consortium
HYV	high-yielding variety
IARC	international agricultural research center
IARI	Indian Agricultural Research Institute
ICAR	Indian Council on Agricultural Research
IFDC	International Fertilizer Development Center
IFPRI	International Food Policy Research Institute
IFSSA	Indian Foundation Seed and Services Association

IIFAD	International Institute for Food, Agriculture, and Development
IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade
IPCC	Intergovernmental Panel on Climate Change
IPM	integrated pest management
IPR	intellectual property rights
IRD	French Research Institute for Development
IRRC	Irrigated Rice Research Consortium
IRRI	International Rice Research Institute
IWRM	integrated water resource management
JICA	Japan International Cooperation Agency
LCC	leaf color chart
MABC	marker-assisted backcrossing
MAFF	Ministry of Agriculture, Forestry, and Fisheries
MARS	marker-assisted recurrent selection
MAS	marker-assisted selection
MRPTA	Myanmar Rice and Paddy Traders Association
MSP	minimum support price
NARES	national agricultural research and extension systems
NCAR	National Center for Atmospheric Research
NERICA	New Rice for Africa
NGO	nongovernment organization
NIA	National Irrigation Administration
NLU	Nong Lam University
NRA	nominal rate of assistance
NRA_O	nominal rate of assistance to output
NSO	National Statistical Organization
OECD	Organization for Economic Cooperation and Development
PDS	Public Distribution System
PhilRice	Philippine Rice Research Institute
PVS	participatory varietal selection
R&D	research and development
RWC	Rice-Wheat Consortium
SAU	state agricultural universities
SeedNet	National Rice Seed Production Network
SRI	System of Rice Intensification
SSA	sub-Saharan Africa
SSNM	site-specific nutrient management
TERI	The Energy Research Institute
TFP	total factor productivity
TLS	truthfully labeled seed
TRQ	tariff rate quota
UAF	University of Agriculture and Forestry
UNCTAD	United Nations Conference on Trade & Development
UPLB	University of the Philippines Los Baños
UPOV	International Union for the Protection of New Varieties of Plants
USAID	United States Agency for International Development
USDA	United States Department of Agriculture
WARDA	West Africa Rice Development Association
WDI	World Development Indicators
WHO	World Health Organization
WTO	World Trade Organization

ha	hectare
kg	kilogram
kg/ha	kilograms per hectare
kg/hour	kilograms per hour
m	meter
ppm	parts per million
t/ha	tons per hectare
t/hour	tons per hour
Tg	teragram

Worldwide, rice is the most important food staple for the poor. It is grown on approximately 155 million hectares and accounts for 19% of the global calorie supply. Although traditionally an Asian crop, rice has long been a staple in parts of Africa and Latin America, and its importance is growing in those regions.

The past decades have seen many changes that will shape the way rice will be produced in the future. These include rapid economic growth, especially in parts of Asia, rising wage rates, increasing diversification of diets, global climate change, and a greater integration of the food economy with other sectors of the global economy, including both energy and financial markets. In the context of these major global trends, there is a need to develop a new vision for future rice farming to strategically position investments in rice research, technology delivery, and the design of policy reforms.

This book presents such a new vision for the future of rice farming. The book is forward-looking and addresses the key strategic questions in the context of major developments in the global economy. The various scholarly contributions in this book examine these strategic questions and lay out a rich menu of options for sustainably improving rice systems and enhancing the overall performance of the global rice economy to reduce poverty and hunger.

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