The culture of rice

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14 Rice: feeding the billions

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Overview

Because rice is critical for food security in so many of the poorest countries, investments in the rice sector should be designed to alleviate poverty and meet the food demands of still growing—and increasingly urbanized—populations. In all rice environments vital ecosystem services—such as biodiversity, groundwater recharge, and flow regulation—in addition to food production should be explicitly recognized and protected. Rice may be relatively benign to the environment compared with other crops: more methane emission but less nitrous oxide, little to no nitrate leaching, and little herbicide use. The food security of many poor consumers depends on the productive capacity of irrigated areas. Increasing water scarcity is expected to further shift rice production to more water-abundant delta areas and to lead to crop diversification and more aerobic soil conditions in rice fields in water-short areas. Investments in these areas should support the adoption of water-saving technologies and the improvement of irrigation supply systems, while sustaining the resource base of the rice fields. There is no single solution for all circumstances, and investments need to be selective and specifically targeted to the different rice environments.

Between a quarter and a third of the world's tapped freshwater resources have already been developed to irrigate rice, the staple food for 3 billion people. More than 90% of the world's rice is produced and consumed in Asia, where rice is a political commodity and where millennia-old practices of growing rice have resulted in specific rice cultures. These cultures need a collective, community-based approach to decisionmaking about the investments in rice fields and about their operation and maintenance. Rice is grown on some 250 million farms, mostly family owned, averaging from less than 0.5 hectares (ha) to 4 ha. Rice grows in a wide range of environments and is productive in many situations where other crops would fail. Worldwide, there are about 79 million ha of irrigated lowlands with average yields of 5 metric tons per hectare, 54 million ha of rainfed lowlands with average yields of 2.3 metric tons per hectare, 14 million ha of rainfed uplands with average yields of 1 metric ton per hectare, and 11 million ha of flood-prone areas with average yields of 1.5 metric tons per hectare. The highly productive irrigated lowlands provide 75% of the world's rice supply. Rice environments also provide unique but as yet poorly understood ecosystem services, such as regulation of water and preservation of aquatic and terrestrial biodiversity.

> The key to achieving food security and alleviating poverty is increasing rice productivity while lowering production costs

Because of the unprecedented growth in production during the past five decades the supply of rice has kept pace with population growth, and the price of rice has fallen and is currently at a historic low. In recent years, however, the growth in productivity has slowed in many countries in Asia. World annual rice production is currently some 550–600 million metric tons (rough, unhusked, and unmilled), and the world market price of top quality (nonaromatic) indica rice has fluctuated at about $250 a metric ton for the past five to six years. The high yields and low prices have helped to alleviate poverty among poor rice consumers.

To meet the food demands of growing populations, rice production needs to continue to increase in coming decades. Although consumer food preferences tend to change as incomes rise, poverty remains in rural irrigated and rainfed rice-growing areas and is increasing in urban areas. To meet the dual challenge of producing enough food and alleviating poverty, more rice needs to be produced at a low unit cost so that producers can be ensured of reasonable profits, poor consumers can have the benefit of low prices, and the environment and ecosystem services can be safeguarded. All this needs to be achieved as urbanization, wages, and the feminization of the rural workforce are increasing and the supply of labor is decreasing. At the same time the productive capacity of rice environments is being threatened by increasing water scarcity in irrigated systems and by droughts, salinity, uncontrolled flooding, and climate change. Approximately 25 million ha of rainfed rice are frequently affected by drought, and 9–12 million ha by salinity, and 15–20 million ha of irrigated rice are projected to suffer some degree of water scarcity over the next 25 years.

The key to achieving food security and alleviating poverty is increasing rice productivity while lowering production costs. Because many stresses on rice production are related to water, increasing water productivity is especially important. The various ecosystem services of rice environments must also be recognized and protected to sustain their capacity to produce food. In irrigated lowlands with ample water supply the development of hybrid rice has the potential to increase the yield of rice plants by 5%–15%. Integrated management approaches could narrow gaps between potential yields and current farmers' yields. A suite of water-saving technologies can help farmers reduce combined losses from percolation, drainage, and evaporation by 15%–20% without reducing yields. The efficiency of irrigation systems can be increased by the conjunctive use of surface water and groundwater and the reuse of percolation and drainage water. We still need to improve our understanding of the effects of increasingly aerobic (nonflooded) field conditions—induced by water scarcity—on the environment, ecosystem services, and the sustainability of rice growing.

In environments prone to drought, salinity, and floods the combination of improved varieties and specific management packages has the potential to increase on-farm yields by 50%–100% in the coming 10 years, provided that investment in research and extension is intensified. Development and delivery of better technologies need to be science based, participatory, gender inclusive, and aware of indigenous farmers' knowledge.

Trends and conditions

Rice, a staple food for almost half the world's population (Maclean and others 2002), grows in a wide range of environments (photo 14.1). More than 90% of global rice production is harvested from irrigated or rainfed lowland rice fields. There is growing awareness that lowland rice environments provide a rich variety of ecosystem services. Rice production also has environmental impacts, largely by releasing or sequestering gases and compounds to the atmosphere and troposphere and by changing the chemical composition of the water flowing through the rice fields. Rice production also has health impacts, mainly mediated through the use of agrochemicals.

Rice is a staple food for almost half the world's population


Photo by International Rice Research Institute

Photo 14.1

The economy of rice

Rice production and consumption. Ninety percent of the world's rice is produced and consumed in Asia (table 14.1), where it accounts for 20%–70% of total caloric intake. Brazil and the United States are also major rice producers; each produces some 10 million metric tons a year. Rice is grown on an estimated 250 million farms, most of them family owned, with country average farm sizes varying from less than 0.5 ha to 4 ha (Hossain and Fischer 1995). In many countries in Asia rice accounts for more than half of the harvested area of all crops.

Historically, an important political objective in most rice-growing countries has been to achieve self-sufficiency in rice production and maintain price stability through domestic procurement and adjustment of stocks. In recent years this has been less necessary because the world rice market has become deeper and more stable (Dawe 2002). International trade in rice is about 7% of production compared with 11% for maize and 18% for wheat (FAOSTAT). With increasing demand for rice (see chapter 2 on trends) and subregional shifts in production, however, we expect that international trade in rice will increase in coming years. Since the 1960s rice imports in West and Central Africa have increased eightfold, to 4 million metric tons a year currently, at an annual cost of more than $1 billion, and now represent more than 25% of the value of total food imports. The relatively cheap imports of rice from Asia pose extra challenges to poor rice farmers in remote areas of Africa.

In the 1960s the combination of new high-yielding rice varieties and increased use of water, fertilizer, and biocides (to protect the crop from pests, disease, and weeds) led to the rapid increase in productivity known as the green revolution. Because of this increased productivity and an increase in cropped area, total rice production over the past 40 years has more than kept pace with the tremendous growth in population in Asia (figure 14.1).

table **14.1** **Rice production and consumption statistics worldwide, 2002**

Country	**Rough rice[a] production** (millions of metric tons)	**Rice area[b]** (thousands of hectares)	**Rough rice yield[c]** (metric tons per hectare)	**Annual milled rice consumption** (kilograms per capita)	**Share of calories from rice in diet** (percent)
China	176.34	28,509	6.19	83	28
India	116.50	40,280	2.89	83	34
Indonesia	51.49	11,521	4.47	149	50
Bangladesh	37.59	10,771	3.49	164	74
Viet Nam	34.45	7,504	4.59	169	65
Thailand	26.06	9,988	2.61	103	41
Myanmar	21.81	6,381	3.42	205	68
Philippines	13.27	4,046	3.28	105	43
Japan	11.11	1,688	6.58	58	22
Brazil	10.46	3,146	3.32	35	12
United States	9.57	1,298	7.37	9	3
Pakistan	6.72	2,225	3.02	18	8
Korea, Rep.	6.69	1,053	6.35	83	29
Egypt	6.11	613	9.97	38	12
Nepal	4.13	1,545	2.67	102	38
Cambodia	3.82	1,995	1.92	149	69
Nigeria	3.19	3,160	1.01	24	9
Iran, Islamic Rep.	2.89	611	4.73	37	12
Sri Lanka	2.86	820	3.49	91	37
Madagascar	2.60	1,216	2.14	95	49
Lao PDR	2.42	783	3.09	168	64
Colombia	2.35	469	5.01	30	12
Malaysia	2.20	677	3.25	73	25
Korea, Dem. Rep.	2.19	583	3.75	70	32
Peru	2.12	317	6.69	49	19
Italy	1.38	219	6.31	6	2
Ecuador	1.29	327	3.93	47	16
Australia	1.19	150	7.95	10	3
Côte d'Ivoire	1.08	470	2.30	63	22
World	577.97	147,633	3.91	57	20

Note: Data are for countries producing more than 1 million metric tons of rice annually.

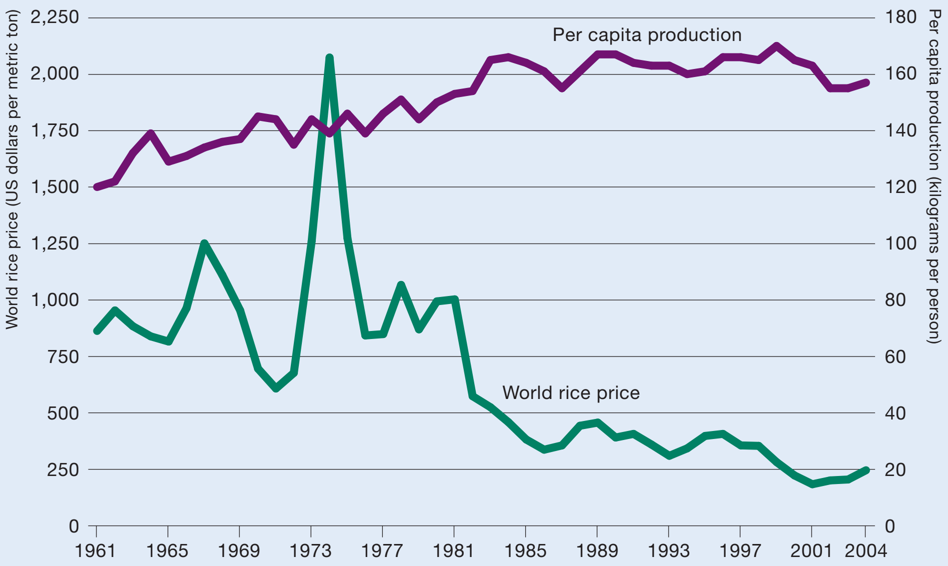
a. Unhulled and unmilled rice.

b. Harvested area, includes multiple cropping.

c. Total production divided by total area averaged across all seasons and areas.

Source: FAOSTAT online updated 14 July 2005 (http://faostat.fao.org/faostat/collections).

figure **14.1** **Rice production has kept pace with population growth in Asia over the past 40 years, while world prices have been falling in the past 25 years**



Note: Rice export prices are adjusted for inflation and expressed in 2004 US dollars.

Source: FAOSTAT online statistical service (http://faostat.fao.org/faostat/collections); World Rice Statistics (www.irri.org/science/ricestat/index.asp); IMF International Financial Statistics online service (www.imf.org)

In recent years, however, the growth in productivity has slowed in many countries in Asia. Declining per capita demand as Asians diversify their diets has also contributed to a stabilization of per capita production.

The falling price of rice. Increasing rice production has led to declining rice prices. World rice prices (adjusted for inflation) fluctuated at around $1,000 a metric ton between 1961 and 1981, declined sharply between 1981 and 1984, and then declined gradually, reaching a record low of less than $250 a metric ton in 2002 (see figure 14.1). Prices rose again slightly in 2004 to about 25% of their level in the early 1980s, with another increase in 2005 as import demand increased.

Shifting comparative advantages. Within Asia the comparative regional advantage in rice production is shifting (Barker and Dawe 2002; Dawe 2005). Before World War II the delta regions (in Bangladesh, Cambodia, eastern India, Myanmar, Thailand, and Viet Nam) held the comparative advantage in rice production and were the main sources of rice exports. The early beneficiaries of the green revolution technology of the 1960s and

1970s were areas where it was possible to irrigate two crops of rice with the construction of reservoir storage. Also benefiting was the northwest Indo-Gangetic Plain, where private investment in groundwater pumping and public investment in irrigation systems and other government policies (subsidies for inputs and minimum price support schemes for grain) favored rice production.

For political reasons and because of the inability to manage floods, the deltas initially were unable to take advantage of the new rice technologies. Over the past 15–20 years, however, with the availability of low-cost pump technology and new cropping systems based on short-duration rice varieties that can avoid the floods, the delta areas have regained their comparative advantage and shown the most rapid growth in rice production and exports. With the improved water control provided by pumps, the delta regions have been able to shift out of low-yielding deep water and floating rice by planting one crop before and one after the floods. In short, rice production is gaining in regions with plentiful water supply and cheap labor relative to areas of water scarcity, and this trend is expected to continue. In the northwest Indo-Gangetic Plain there are now grave concerns about the sustainability of irrigated rice production because of rapidly falling groundwater tables and the government's need to reduce the large fiscal costs associated with policies that promote rice production.

> Rice grows in a wide range of environments and is productive in many situations where other crops would fail

Changes in demography and the rice economy. As economies develop, the rural sector undergoes major changes. The younger members of rural communities, particularly the men, leave in search of jobs in urban areas or overseas and send remittances back to their rural homes. These rural economies are becoming older and more feminized (box 14.1), and this trend is likely to continue. In some countries, especially in Africa, HIV/AIDS is also exacting a toll on the rural labor force. As a consequence, labor availability is declining and wages are increasing in many rice-growing areas (Barker and Dawe 2002). Farm employment is less attractive, and labor is harder to find at peak periods for key operations such as transplanting, weeding, and harvesting. With rising wages and labor shortages, mechanization is becoming more common for both land preparation and harvesting, especially in irrigated areas. Also, farmers are shifting from hand weeding to the use of herbicides, and from transplanting to direct seeding. By the late 1990s an estimated one-fifth of the rice area in Asia was direct seeded (Pandey and Velasco 2002), and this proportion is expected to rise.

The rice environments

Rice grows in a wide range of environments and is productive in many situations where other crops would fail. Most classifications of rice environments are based on hydrological characteristics (Huke and Huke 1997; Maclean and others 2002). Irrigated lowland rice is grown in bunded fields with ensured irrigation for one or more crops a year. Farmers generally try to maintain 5–10 centimeters (cm) of water ("floodwater") on the field. Rainfed lowland rice is grown in bunded fields that are flooded with rainwater for at least part of the cropping season to water depths that exceed 100 cm for no more than 10 days. In both irrigated and rainfed lowlands fields are predominantly puddled (harrowing or rotavating under shallow submerged conditions) and plants are transplanted. Deepwater rice and floating rice are found in flood-prone environments, where the fields suffer periodically from excess

box 14.1 Gender issues

As in agriculture in general, gender issues in rice production are complex and site specific. Women participate in various degrees in the cultivation of rice and often have specific tasks such as transplanting, weeding, or harvesting. In Central and West Africa women constitute the majority of upland rice farmers.

Increasing water scarcity and technological response options affect women in different ways, depending on whether they are paid or unpaid laborers. For example, a shift from transplanting to direct seeding may specifically affect the livelihoods of women since transplanting is their traditional task in most African and Asian societies. If they are unpaid laborers, the shift will remove the drudgery and back-breaking burden of transplanting. But if they are paid laborers, it will deprive them of a source of income. The same reasoning holds for weeding. Water scarcity and response options such as alternate wetting and drying and aerobic rice may promote weed growth and increase the need for manual weeding. In Africa women's preference for using water to control weeds arises from their being unpaid laborers.

Thus it is important to include a gender perspective in the development of alternative response options or technologies of rice production. The same holds true for the development and deployment of new rice varieties. Women should be specifically included in activities such as participatory varietal selection, as they often have different perceptions of relevant crop traits, for example, grain quality and feed quality of the straw (in many cases, it is women who tend the livestock).

water and uncontrolled, deep flooding. Upland rice is grown under dryland conditions (no ponded water) without irrigation and without puddling, usually in nonbunded fields.

Irrigated environments. Worldwide, about 79 million ha of irrigated lowland rice provide 75% of the world's rice production (Maclean and others 2002). Some 56% of the world's irrigated area of all crops is in Asia, where rice accounts for 40%–46% of the irrigated area of all crops (Dawe 2005). Rice occupies 64%–83% of the irrigated area in Southeast Asia, 46%–52% in East Asia, and 30%–35% in South Asia. At the field level rice receives up to 2–3 times more water per hectare than other irrigated crops (Tuong, Bouman, and Mortimer 2005), but an unknown portion of the water losses is reused by other fields downstream (Loeve and others 2004a). Assuming a reuse rate of 25%, we estimate that irrigated rice receives 34%–43% of the world's irrigation water and some 24%–30% of the world's developed freshwater resources.

Irrigated rice is grown mostly with supplementary irrigation in the wet season and is reliant entirely on irrigation in the dry season. The proportion of the Asian rice area that is irrigated (excluding China, where essentially all rice is irrigated) increased substantially from the late 1970s (35%) to the mid-1990s (44%) because of an increase in the irrigated area coupled with a large decline in upland and deepwater rice cultivation (Dawe 2005). In many irrigated areas rice is grown as a monoculture with two crops a year. However, significant areas of rice are also grown in rotation with a range of other crops, including about 15–20 million ha of rice-wheat systems. At the turn of the millennium, country average irrigated rice yields in Asia ranged from 3 metric tons to 9 metric tons per hectare, with an overall average of about 5 metric tons per hectare.

Rainfed environments. Worldwide, about 54 million ha rainfed lowlands supply about 19% of the world's rice production, and 14 million ha rainfed uplands contribute about 4% of the world's total rice production (Maclean and others 2002). Rainfed rice environments experience multiple abiotic stresses and high levels of uncertainty in timing, duration, and intensity of rainfall. Some 27 million ha of rainfed rice are frequently affected by drought, the largest, most frequently, and severely affected areas being eastern India (about 20 million ha) and northeastern Thailand and Lao PDR (7 million ha) (Huke and Huke 1997). Drought is also widespread in Central and West Africa. Further constraints arise from the widespread prevalence of problem soils with poor physical and chemical properties. Country average rice yields are only some 2.3 metric tons per hectare in the lowlands and 1 metric ton per hectare in the uplands.

Rainfed rice environments experience multiple abiotic stresses and high levels of uncertainty in timing, duration, and intensity of rainfall

In *rainfed lowlands* small to moderate topographic differences can have important consequences for water availability, soil fertility, and flooding risk. The unpredictability of rainfall often results in field conditions that are too dry or too wet. Besides imposing water-related stresses on crop growth, these conditions prevent timely and effective management operations such as land preparation, transplanting, weed control, and fertilizer application. If such operations are delayed or skipped, yield losses can be large, even though the plants have not suffered physiological water stress.

Rainfed uplands are highly heterogeneous, with climates ranging from humid to subhumid, soils from relatively fertile to highly infertile, and topography from flat to steeply sloping. With low population density and limited market access, shifting cultivation with long (more than 15 years) fallow periods was historically the dominant land-use system. Increasing population and improved market access have put pressure on these systems, but shifting cultivation with 3–5 year fallow periods still accounts for 14% of the Asian upland rice area, mainly in northeastern India, Lao PDR, and Viet Nam. However, some 70% of Asia's upland rice areas have made the transition to permanent systems where rice is grown every year and is closely integrated with other crops and livestock. In Central and West Africa, the rice belt of Africa, upland areas represent about 40% of the area under rice cultivation and employ about 70% of the region's rice farmers. As market access remains limited, most of the world's upland rice farmers tend to be self-sufficient by producing a range of agricultural outputs.

Research efforts to increase yields and yield stability in rainfed environments, limited in the past, have been intensified in the past 10–15 years, especially in the lowlands. Together with socioeconomic developments this has considerably improved rainfed systems through better access to information and markets for inputs and outputs, more opportunities for off-farm income, improved varieties, and (partial) mechanization.

Flood-prone environments. Flood-prone environments include deepwater areas submerged under more than 100 cm of water from 10 days to a few months, areas that are affected by flash floods of longer than 10 days, extensive low-lying coastal areas where plants are subject to daily tidal submergence, and areas with problem soils (acid-sulphate and sodicity) where the problem is often excess water but not necessarily prolonged submergence (Maclean and others 2002). Altogether, there are some 11 million ha of flood-prone rice areas with average yields of about 1.5 metric tons per hectare.

Salinity-prone environments. Salinity is widespread in coastal areas, and salinity, alkalinity, or sodicity is widespread in inland areas of arid regions (Garrity and others 1986). These problems occur in irrigated as well as rainfed environments. In coastal areas rice can suffer from salinity because of seawater ingress during high tides. In inland areas salinity arises from salt deposits present in the soil or bedrock or from the use of salty irrigation water. In the mid-1980s an estimated 1.3 million ha of rice-growing areas were affected by salinity or alkalinity. Today, we estimate that some 9–12 million ha are affected, with 5–8 million ha in India; 1 million ha each in Bangladesh, Thailand, and Viet Nam; and about 1 million ha in Indonesia and Myanmar combined.

More than 90% of the world's rice production is harvested from irrigated or rainfed lowland (or paddy) rice fields

Water use and water productivity

More than 90% of the world's rice production is harvested from irrigated or rainfed lowland (or paddy) rice fields (photo 14.2). Traditionally, lowland rice is raised in a seedbed and then transplanted into a main field that is kept under continuous (irrigated) or intermittent (rainfed) ponded water conditions to help control weeds and pests. Land preparation consists of soaking, plowing, and puddling. Puddling is also done for weed control, to reduce soil permeability and percolation losses, and to ease field leveling and transplanting. The water balance of lowland rice, because of its flooded nature, is different from that of other cereals such as wheat (box 14.2).

Photo by B.A.M. Bouman

Photo 14.2

Water use. Total seasonal water input to rice fields (rainfall plus irrigation, but excluding capillary rise, which is rarely quantified) is up to 2–3 times more than that for other cereals (Tuong, Bouman, and Mortimer 2005). It varies from as little as 400 mm per field in heavy clay soils with shallow groundwater tables that supply water for crop transpiration by capillary rise, to more than 2,000 mm in coarse-textured (sandy or loamy) soils with deep groundwater tables (Bouman and Tuong 2001). About 1,300 millimeters (mm) seems to be a typical average value for irrigated rice in Asia. Nonproductive outflows of water by runoff, seepage, and percolation are about 25%–50% of all water input in heavy soils with shallow water tables of 20–50 cm depth and 50%–85% in coarse-textured soils with deep water tables of 1.5 meter depth or more. Though runoff, seepage, and percolation are losses at the field level, they are often captured and reused downstream and do not necessarily lead to true water depletion at the irrigation area or basin scales. However, the proportion and magnitude of reuse of these flows are not generally known.

Water productivity. Modern rice varieties, when grown under flooded conditions, are similar in transpiration efficiency to other C_3 cereals (box 14.3) such as wheat, at about 2 kilograms (kg) grain per cubic meter of water transpired (Bouman and Tuong 2001). What few data are available indicate that water productivity of rice as measured by evapotranspiration is also similar to that of wheat, ranging from 0.6 kg to 1.6 kg grain per cubic meter of evapotranspired water, with a mean of 1.1 kg grain per cubic meter (Zwart and Bastiaanssen 2004). The higher evaporation rates from the water layer in rice than from the underlying soil in wheat are apparently compensated for by the higher yields of rice. Maize, as a C_4 crop, has a higher evapotranspiration efficiency (ranging from 1.1 kg to 2.7 kg grain per cubic

box **14.2** Water flows from a rice field

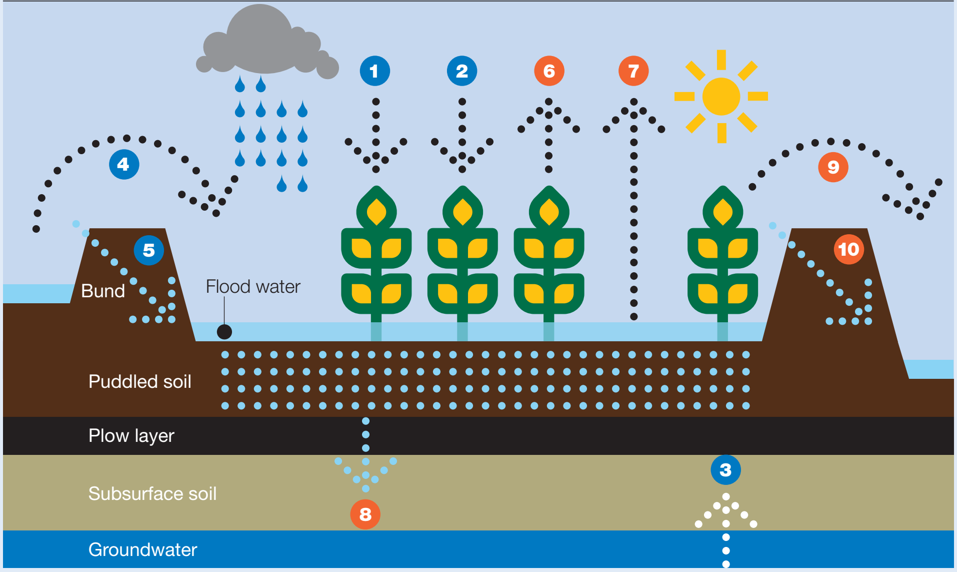
For lowland rice, water is needed to prepare the land and to match the outflows seepage, percolation, and evapotranspiration during crop growth (see figure). The amount of water used for wet land preparation can be as low as 100–150 mm (depth of water per surface area) when the time lag between soaking and transplanting is only a few days or when the crop is directly wet seeded. But it can be as high as 940 mm in large-scale irrigation systems with poor water control, where the time lag between soaking and transplanting is as long as two months (Tabbal and others 2002).

After the crop is established, the soil is usually kept ponded until shortly before harvest. *Seepage* is the lateral subsurface flow of water, and *percolation* is the flow of water down below the root zone. Typical combined values for seepage and percolation vary from 1–5 mm a day in heavy clay soils to 25–30 mm a day in sandy and sandy loam soils (Bouman and Tuong 2001). *Evaporation* is water lost into the air as vapor from the ponded water layer or from the surface of the soil, and *transpiration* is water released into the air as vapor through the plants. Typical combined evapotranspiration rates of rice fields are 4–5 mm a day in the wet season and 6–7 mm a day in the dry season, but can be as high as 10–11 mm a day in subtropical regions before the onset of the monsoon. *Over-bund flow* or *surface runoff* is the spillover when water depths rise above the bunds of the fields. Seepage, percolation, evaporation, and over-bund flow are all nonproductive flows of water and are considered losses at the field level.

Water inflows and outflows in a lowland rice field

Inflows
1 Rainfall
2 Irrigation
3 Capillary rise
4 Over-bund inflow
5 Seepage from higher field

Outflows
6 Transpiration by the crop
7 Evaporation from the water layer or soil
8 Percolation
9 Over-bund outflow
10 Seepage into lower field



box 14.3 The rice plant

All plants fall into two main categories according to how they assimilate carbon dioxide into their system. Rice, together with cereals such as wheat and barley, belongs to the group of C_3 grasses, whereas cereals such as maize and sorghum belong to the group of C_4 grasses. The C_4 species have a more efficient photosynthetic pathway than the C_3 species and produce more biomass per unit of intercepted radiation and per unit of transpiration. The wetland ancestry of rice is reflected in a number of morphological and physiological characteristics that are unique among crop species and set it apart from other cereals (Lafitte and Bennet 2002).

Rice is extremely sensitive to water shortage. When soil water content drops below saturation, growth and yield formation are affected, mainly through reduced leaf surface area, photosynthesis rate, and sink size. The most sensitive stage to drought is around flowering (see photo), when drought induces spikelet sterility.

While rice is adapted to water logging, complete submergence can be lethal. Most rice varieties can survive complete submergence of only 3–4 days, though some rainfed lowland rice can survive up to 10 days. Germination especially is sensitive to submergence. During later vegetative development rice can adapt to complete submergence, though it hastens the plant's energy depletion and increases mortality. Tall plants tend to lodge (fall down) when the water level recedes, resulting in yield losses and poor grain quality.

Rice is a salt-sensitive crop and yield reductions start at electric conductivity values of 3 decisiemens (dS) per meter, rising to 50% at 6 dS per meter and 90% at 10 dS per meter (Shannon 1997). For comparison, yield reductions start at about 2 dS per meter for maize, 6 dS per meter for wheat, and 8 dS per meter for barley. Rice is relatively tolerant of salinity during germination, active tillering, and toward maturity but is sensitive during early seedling and reproductive stages.


Photo by B.A.M. Bouman

Rice is especially sensitive to drought at flowering

meter of water, with a mean of 1.8). The water productivity of rice for total water input (irrigation plus rainfall) ranges from 0.2 kg to 1.2 kg grain per cubic meter of water, with an average of 0.4, about half that of wheat (Tuong, Bouman, and Mortimer 2005).

Unique ecosystem services

Though only a few studies have been conducted so far, awareness is growing that lowland rice environments provide an unusually rich variety of ecosystem services. Studies on the value of rice ecosystems beyond crop production have recently received a boost by the threat to rice price supports and trade restrictions in many countries presented by multilateral trade negotiations under the World Trade Organization (PAWEES 2005).

Provisioning services. The most important provisioning function of the rice environment is the production of rice. Irrigated rice culture has been sustained for thousands of years in various parts of Asia. Recent findings of 30 long-term continuous cropping experiments at 24 sites in Asia confirm that, with an assured water supply, lowland rice fields are extremely sustainable and able to produce continuously high yields (Dawe and others 2000). Flooding has beneficial effects on soil acidity; phosphorus, iron, and zinc availability; and biological nitrogen fixation (Kirk 2004). Other provisioning services are the raising of fish and ducks in rice fields, ponds, or canals. Frogs and snails are collected for consumption in some countries.

Many traditional festivals and religious practices are associated with rice cultivation

Regulating services. Bunded rice fields may increase the water storage capacity of catchments and river basins, lower the peak flow of rivers, and increase groundwater flow. For example, in 1999 and 2000, 20% of the floodwater in the lower Mekong River Basin was estimated to be temporarily stored in upstream rice fields (Masumoto, Shimizu, and Hai 2004). The many irrigation canals and reservoirs associated with the lowland rice landscape have a similar buffering function.

Other regulatory services of bunded rice fields and terraces include trapping of sediments and nutrients and the prevention or mitigation of land subsidence, soil erosion, and landslides. Percolation from rice fields, canals, and storage reservoirs recharges groundwater systems. Such recharge may also provide a means of sharing water equitably among farmers, who can pump from shallow aquifers at relatively low cost rather than suffer from inequitably shared or poorly managed surface irrigation systems. The moderation of air temperature by rice fields has been recognized as a regulating service in peri-urban areas where paddy and urban land are intermingled. This function is attributed to relatively high evapotranspiration rates that lower the ambient temperature of the surrounding area in the summer and result in lateral heat emission from the water body in winter. Rice can be used as a desalinization crop because of its ability to grow well under flooded conditions where continuously percolating water leaches salts from the topsoil.

Photo by International Rice Research Institute

Photo 14.3

Supporting services. Flooded rice fields and irrigation channels form a comprehensive water network, which together with their contiguous dry land provides a complex mosaic of landscapes. The Ramsar Convention on wetlands classified irrigated rice land as a human-made wetland (Ramsar Convention Secretariat 2004). Surveys show that such landscapes sustain a rich biodiversity, including unique and threatened species (Fernando, Goltenboth, and Margraf 2005), and enhance biodiversity in urban and peri-urban areas. In parts of the United States, such as California, rice fields are ponded in winter and used to provide habitat for ducks and other water birds.

Cultural services. The cultural services of rice environments are especially valued in Asian countries, where rice has been the main staple food and the single most important source of employment and income for rural people for centuries if not millennia. Many old kingdoms as well as small communities have been founded on the construction of irrigation facilities to stabilize rice production. The collective approach needed to invest in rice systems (construction of terraces, tank systems for irrigation) and operation and maintenance (terraces, but also cropping calendar) requires strong community approaches. 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). Many traditional festivals and religious practices are associated with rice cultivation (photo 14.3), and rice fields are valued for their scenic beauty. Rice is also an integral part of the history and culture of Africa, where it has been grown for more than 3,000 years.

Environmental impacts

Rice production affects the environment mainly by releasing or sequestering gases or compounds that are active in the atmosphere or troposphere and by changing the chemical composition of the water flowing through rice fields. Rice is in turn affected by environmental changes, such as global climate change (box 14.4).

Ammonia volatilization. Ammonia volatilization is the major pathway of nitrogen loss from applied nitrogen fertilizer in rice systems. Across irrigated environments in Asia, nitrogen fertilizer input averages 118±40 kg per hectare, with the highest levels in southern China, at up to 300 kg per hectare (Witt and others 1999). In tropical transplanted rice nitrogen losses from ammonia volatilization can be 50% or higher, while in direct-seeded rice in temperate regions losses are generally negligible because most of the fertilizer is incorporated into the soil before flooding. Ammonia-nitrogen volatilizations from lowland rice fields are estimated at 3.6 teragrams (Tg) a year (compared with 9 Tg a year emitted from all agricultural fields worldwide), which is some 5%–8% of the estimated 45–75 Tg of globally emitted ammonia-nitrogen each year (Kirk 2004). The magnitude of ammonia volatilization depends largely on climatic conditions, field water management, and method

box 14.4 Projected effects of climate change on rice

Climate change is expected to raise carbon dioxide levels and temperatures and increase the frequency of extreme climatic events, such as storms, droughts, and heavy rainfall in monsoon climates that will increase the incidence of flooding. Rising sea levels are expected to increase flood risk and salinity intrusion in rice growing environments in delta areas (Wassman and others 2004).

Simulations for the major rice-growing regions of Asia find that yield decreases 7% for every 1° Celsius (C) rise in temperature above current mean temperature at existing atmospheric carbon dioxide concentration. Elevated carbon dioxide levels increase yield and water productivity by increasing dry matter production, number of panicles, and grain filling percentage (Ziska and others 1997). However, elevated carbon dioxide also increases spikelet susceptibility to high temperature–induced sterility. Overall, the beneficial effect of elevated carbon dioxide on the yield and water productivity of rice disappears under high temperatures. Recently, yield reduction in rice has been correlated with increased nighttime temperatures: grain yield declined 10% for each 1°C increase in growing-season minimum temperature in the dry season in irrigated tropical rice (Peng and others 2004).

Intraspecific variations in yield response to changes in carbon dioxide levels in rice could be exploited to maximize the beneficial effect of increased carbon dioxide levels. Similarly, genotypic variation in the sensitivity to warm nighttime temperature and high daytime temperatures opens up the possibility of developing rice varieties that are less sensitive to higher temperatures. Selection of rice varieties that flower early in the morning can be an effective way to avoid high daytime temperatures and reduced spikelet sterility.

of nitrogen fertilizer application. Volatilized ammonium can be deposited on the earth by rain. This can be a beneficial source of (free) nitrogen fertilizer in agricultural lands, but it can also lead to soil acidification and unintended nitrogen inputs into natural ecosystems.

Greenhouse gases. Of the three main greenhouse gases, rice production reduces carbon dioxide levels through carbon sequestration and has relatively low nitrous oxide emissions but relatively high methane emissions.

> Rice contributes 3%–10% to global methane emissions

Carbon sequestration. Rice soils that are flooded for long periods of the year tend to sequester carbon, even with the complete removal of above-ground plant biomass (Bronson and others 1997). Significant carbon accumulation results from biological activity in the soil-floodwater system. Average soil organic carbon content in irrigated double and triple rice systems in Asia is about 14–15 grams of carbon per kilogram in the upper 20–25 cm of soil (Dobermann and others 2003). Assuming an average bulk density of about 1.25 metric tons per cubic meter of soil and a physical land area of about 24 million ha, these monoculture systems alone store about 45 metric tons of carbon per hectare or a total of 1.1 petagrams of carbon (109 metric tons) in the topsoil. Additional carbon is stored in other irrigated rice systems (such as single rice and rice-maize), although typically in smaller amounts than in monoculture systems. However, reliable information on soil carbon stocks is not available for rice systems in most countries, and it is not known how soil organic carbon levels will change in response to changing climate or management practices.

Nitrous oxide. Few accurate assessments have been made of nitrous oxide emissions from rice fields, so the contribution to global emissions has not been assessed. In irrigated rice systems with good water control, nitrous oxide emissions are very small except when nitrogen fertilizer rates are excessively high (Bronson and others 1997; Wassmann and others 2000). In irrigated rice fields the bulk of nitrous oxide emissions occur during fallow periods and immediately after flooding of the soil at the end of the fallow period. In rainfed systems, however, nitrate accumulation in aerobic phases might contribute to considerable emission of nitrous oxide.

Methane. In the early 1980s it was estimated that lowland rice fields emitted 50–100 Tg of methane per year, or about 10%–20% of the then-estimated global methane emissions (Kirk 2004). Recent measurements show that many rice fields emit substantially less methane, especially in northern India and China, both because methane emissions have decreased with changes in rice production systems and because techniques for upscaling greenhouse gas emissions have improved with the use of simulation models and geographic information systems (GIS) (Matthews and others 2000).

The uncertainty in methane emissions from rice fields is among the highest of all sources in the global methane budget. Current estimates of annual methane emissions from rice fields are in the range of 20–60 Tg, or 3%–10% of global emissions of about 600 Tg (Kirk 2004). Estimates of annual methane emissions from the principal rice producers China and India are in the range of 10–30 Tg. The magnitude and pattern of methane emissions from rice fields are determined mainly by the water regime and organic inputs and to a lesser extent by soil type, weather, tillage practices, residue management, fertilizer use, and rice cultivar (Bronson and others 1997; Wassmann and others 2000). Use of organic manure generally enhances methane emissions. Flooding of the soil is a prerequisite for sustained emissions of methane. Mid-season drainage, a common irrigation practice in the major rice-growing regions of China and Japan, greatly reduces methane emissions. Similarly, rice environments with an uneven supply of water, such as rainfed environments, have a lower emission potential than environments where rice is continuously flooded.

Surface water pollution. The changes in water quality associated with rice production may be positive or negative, depending on the quality of the incoming water and on management practices relating to fertilizer and biocide use, among others. The quality of the water leaving rice fields may be improved by the capacity of the wetland ecosystem to remove nitrogen and phosphorus. On the other side of the ledger, nitrogen transfers from flooded rice fields by direct flows of dissolved nitrogen in floodwater through runoff or drainage warrant more attention. The pollution of groundwater is covered below in the discussion of human health.

Contamination of groundwater with arsenic has recently emerged as a major health issue in Asia

Salinization. Percolating water from lowland rice fields usually raises the water table. Where the groundwater is saline, this can salinize the rootzone of nonrice crops in the area and cause waterlogging and salinity in lower areas in the landscape, such as in parts of Australia and the northwest Indo-Gangetic Plain. Where irrigation water is relatively fresh, flooded rice can be used in combination with adequate drainage to leach salts that had previously accumulated under nonrice crops out of the rootzone, as in parts of northern China, and to reclaim sodic soils when used in combination with gypsum, as in parts of the northwest Indo-Gangetic Plain.

Rice and health—pollution and nutrition

Many of the rural poor in Asia obtain water for drinking and household use from shallow aquifers under agricultural land. Among the agrochemicals that pose the greatest threats to domestic use of groundwater are nitrate and biocide residues. In addition, contamination of groundwater with arsenic has recently emerged as a major health issue in Asia. Other health aspects concern malnutrition and vector-borne diseases related to rice production.

Nitrates. Nitrate leaching from flooded rice fields is normally negligible because of rapid denitrification under anaerobic conditions. In the Philippines, for example, nitrate pollution of groundwater under rice-based cropping systems exceeded the 10 milligrams (mg) per liter limit for safe drinking water only when highly fertilized vegetables were included in the cropping system (Bouman, Castañeda, and Bhuiyan 2002). In the Indian Punjab, however, an increase in nitrate of almost 2 mg per liter was recorded between 1982 and 1988, with a simultaneous increase in nitrogen fertilizer use from 56 kg to 188 kg per hectare, most of it on combined rice-wheat cultivation (Bijay-Singh, Sadana, and Arora 1991). The relative contribution to this increase from rice, however, is not clear.

Biocides. Mean biocide use in irrigated rice systems varies from some 0.4 kg active ingredients per hectare in Tamil Nadu, India, to 3.8 kg per hectare in Zhejiang Province, China (Bouman, Castañeda, and Bhuiyan 2002). In the warm and humid conditions of the tropics volatilization is the major process of biocide loss, especially when biocides are applied on the water surface or on wet soil. Relatively high temperatures favor rapid transformation of the remaining biocides by photochemical and microbial degradation, but little is known about the toxicity of the residual components. In case studies in the Philippines mean biocide concentrations in groundwater under irrigated rice-based cropping systems were one to two orders of magnitude below the single (0.1 micrograms per liter) and multiple (0.5 micrograms per liter) biocide limits for safe drinking water, although temporary peak concentrations of 1.14–4.17 micrograms per liter were measured (Bouman, Castañeda, and Bhuiyan 2002).

Biocides and their residues may be directly transferred to open water bodies through drainage water that flows overland from rice fields. The potential for water pollution from biocides is greatly affected by field water management. Different water regimes result in different pest and weed populations and densities, which farmers may combat with different amounts and types of biocides. In traditional rice systems relatively few herbicides are used because puddling, transplanting, and ponding water are effective weed control measures.

> Human micronutrient deficiencies are relatively severe in areas where rice is the major staple

Arsenic. Arsenic in groundwater has been reported in many countries in Asia. Severe problems of aresenicosis occur in rural areas in Bangladesh and in West Bengal in India. In the past two decades the number of shallow tubewells for irrigation in these areas has increased dramatically, and the dry season rice production (Boro rice) depends heavily on groundwater. It is unclear whether groundwater extraction for irrigation influences arsenic behavior in the shallow aquifers, but irrigation from arsenic-contaminated aquifers may pose several risks. Arsenic accumulates in the topsoil as a result of irrigation water input. Because rice fields receive higher inputs of irrigation water than other crops, they accumulate more arsenic than other fields. Moreover, arsenic is potentially more bioavailable under flooded than nonflooded conditions.

It is not yet possible to predict arsenic uptake by plants from the soil, and significant correlations are not often found between total arsenic in the soil and in plants (Abedin, Cotter-Howells, and Meharg 2002). Arsenic that is taken up by rice is found mostly in roots and shoot tissue, and very little in the grains. In Bangladesh no milled rice samples have been found to contain more arsenic than the government threshold of 1 part per million for safe consumption, although straw samples have, raising concerns about arsenic toxicity in animal feed.

Arsenic in the soil may also affect crop production, but this aspect has not received much attention yet, and understanding of the long-term aspects of arsenic in agriculture is too limited to assess the risks. Water-saving irrigation techniques for rice (such as alternate wetting and drying irrigation and aerobic rice) reduce the irrigation inputs and arsenic contamination risk of the topsoil. As the soil becomes more aerobic, the solubility and uptake of arsenic is also reduced.

Nutrition. Human micronutrient deficiencies are relatively severe in areas where rice is the major staple. Increasing the density of provitamin A carotenoid, iron, and zinc in rice can help alleviate these deficiencies, especially among the urban and rural poor people who have little access to alternatives such as enriched foods and diversified diets. Promising examples are the development of golden rice to combat vitamin A deficiency (Potrykus 2003) and of iron-rich rice to combat iron deficiency (Haas and others 2005), although it is still debated whether such increases in the endosperm are sufficient to significantly affect human nutrition. To drive the adoption of micronutrient-rich varieties, the improved traits will need to be combined with other traits that are attractive to farmers, such as tolerance to drought, salinity, or submergence.

> Future demand for rice will depend on population growth and on the age structure, income, and urbanization of the population

Vector-borne diseases. Irrigated rice fields can serve as breeding sites for mosquitoes and snail intermediate hosts capable of transmitting human parasites (see also chapter 9 on irrigation). In particular, before transplanting and after harvest, puddles in rice fields are attractive breeding grounds for the mosquito *Anopheles gambiae,* Africa's most efficient malaria vector. Factors that determine whether the introduction of irrigated rice increases or reduces the incidence of malaria are known, and technical options exist to mitigate this impact, including alternate wetting and drying irrigation. Moreover, countries such as Sri Lanka have made great strides in controlling epidemics through broad-based public health campaigns. Japanese B-encephalitis is highly correlated with rice irrigation in Asia, especially where pigs are also reared, as in China and Viet Nam. Again, alternate wetting and drying can help reduce the breeding of vectors (Keiser and others 2005).

The challenges

The main challenge facing most rice-producing and -consuming countries is to provide sufficient affordable food for growing and urbanizing populations and to alleviate rural and urban poverty. This has to be done under increasing pressure on land, water, and labor resources that threaten the sustainability of the rice production base. At the same time, the importance of the nonfood services provided by rice environments is increasingly recognized. And the negative externalities of rice production on the environment need to be minimized where water scarcity forces production to rely on more aerobic systems rather than permanent flooding.

Feeding the billions

Future demand for rice will depend on population growth and on the age structure, income, and urbanization of the population. Annual population growth in rice-producing Asia was about 1.2% from 2000 to 2005 but is forecast to decline to 0.1% by 2050 (FAOSTAT). As incomes rise, particularly in urban areas, per capita rice consumption declines. At the national level per capita consumption is declining not only in East Asia (China, Japan, and the Republic of Korea) but also in Malaysia and Thailand. For the next two decades, however, an increasing demand for rice in response to increasing populations is still expected to outstrip this decline in per capita consumption. Assuming a mild decline in world rice prices, rice demand in Asia is expected to grow by about 1% a year until 2025 (Sombilla, Rosegrant, and Meijer 2002). In West and Central Africa demand for rice is currently growing at 6% a year, faster than anywhere else in the world. This growth is largely the result of urbanization and changing consumer preferences favoring rice.

Alleviating poverty

Despite declining poverty rates in the past few decades in much of Asia, the absolute number of poor people has declined very little, especially in South Asia and Sub-Saharan Africa. Poverty still exists in rural areas in both the irrigated and the rainfed rice environments. Asia is rapidly urbanizing, and more people will shift from being net rice producers to net rice consumers. Also, the total number of urban poor people is expected to increase. A major challenge will be not only to produce more rice, but to keep its price low to improve the well-being of poor people (box 14.5). Because a low rice price depresses the profitability of rice farming, particularly for small-scale producers, the simultaneous challenge is to decrease the cost of rice production (per kilogram) to boost the profitability of rice farming. Support schemes for small farmers can also help in coping with low prices.

Sustaining the resource base and protecting the environment

Irrigated environments. Worldwide, water for agriculture is increasingly scarce. Although there is no systematic definition, inventory, or quantification of water scarcity in rice-growing areas, there is evidence that water scarcity is encroaching on irrigated lowlands. It is estimated that by 2025, 15–20 million ha of irrigated rice will suffer some degree of water scarcity

box **14.5** | Rice's contribution to poverty alleviation

Access to irrigation, fertilizer, and the high-yielding varieties of the green revolution increased productivity and profits and contributed to food security and poverty reduction among farmers with irrigated land. The growth in rice production outstripped the growth in population, thus lowering prices (see figure 14.1), which reduced the daily expenses for food of poor consumers such as the rural landless, urban laborers, fishers, and farmers of crops other than rice. The contribution of lower prices is not trivial, because many of these people spend 20%–40% of their income on rice alone. Furthermore, low rice prices make labor costs in the industrial and service sectors more competitive, fueling job growth and catalyzing economic development (Dawe 2000).

But low rice prices can hurt some farmers, especially those who have not adopted modern varieties and thus have not benefited from productivity increases. Indeed, despite the successes of the green revolution poverty or hunger still occurs among considerable numbers of rice farmers within irrigated areas (Magor 1996), because even in highly productive systems it is difficult to escape poverty with only a small plot of land. Poverty is still widespread among farmers in rainfed areas, especially in the remote uplands of Laos, Nepal, Viet Nam, and northeastern India and in Sub-Saharan Africa. For many poor farming households, however, increasing rice productivity is often the first step out of poverty as it provides food security and frees up land and labor resources (Hossain and Fischer 1995). With increased rice yields part of the farm land can be taken out of rice production and converted into more profitable cash crops. Freed-up labor can be invested in off-farm employment. Increased income can be used to invest in the education of children, which is a potential pathway out of farming and poverty.

(Tuong and Bouman 2003). Even in areas generally considered water abundant, several case studies indicate that there are local hotspots of water scarcity. This water scarcity is expected to further shift rice production to more water-abundant delta areas, to lead to crop diversification, and to result in more aerobic soil conditions in rice fields in water-short areas.

There are indications that soil-borne pests and diseases (such as nematodes, root aphids, and fungi) and nutrient disorders occur more in nonflooded than in flooded rice systems (George and others 2002). Rice that is not permanently flooded tends to have more weed growth and a broader weed spectrum than rice that is (Mortimer and Hill 1999), likely leading to more frequent use of herbicides. With less water the numbers and types of pests and predators may change as well as predator-pest relationships. Possible shifts in the use of pesticides by farmers in response to these changes, and what this means for the environment, are as yet unknown.

Less ammonia volatilization and methane emissions are expected under nonflooded conditions, but also higher nitrous oxide emissions and more leaching of nitrate. The net greenhouse gas impact is as yet unknown. While direct evidence from converted paddy fields is still missing, it is likely that growing rice under increasingly aerobic conditions will reduce soil carbon contents and release carbon dioxide into the atmosphere. This change in soil organic matter will be accompanied by changes in the microbial community, shifting from predominately anaerobic to aerobic organisms. It is not clear how these changes will affect soil fertility, if at all. The transformation of rice fields to upland crops will likewise have consequences for sustainability and the environment.

Better understanding of the ecosystem services of the rice environment is needed


Photo by B.A.M. Bouman

Photo 14.4

Rainfed environments. A major challenge is to minimize the negative environmental consequences of intensification in rainfed environments. Intensification through increased fertilizer use, cropping intensity, and changes in methods of crop establishment will affect soil and environmental processes. Increased productivity, based initially on better varieties and subsequently on unbalanced use of inorganic fertilizer and reduced organic fertilizer, changes nutrient balances and increases the mining of soil nutrients. Reports of rapidly emerging severe nutrient deficiencies after intensification testify to the relative fragility of rainfed systems because of frequently low natural soil fertility and low buffering capacity.

Valuing the ecosystem services of rice environments

There is growing recognition of the need for a better understanding of the ecosystem services of the rice environment (photo 14.4). Although some methodologies have been developed to measure and estimate different services of agricultural systems, quantifying and valuing the positive and negative externalities are still major challenges. Many countries lack relevant data at the appropriate geographic level.

Response options

Most of the increase in rice production to meet food security and alleviate poverty has to come from higher yields on existing cropland (irrigated and rainfed) to avoid environmental degradation, destruction of natural ecosystems, and loss of biodiversity (Tilman and others 2002). Most of the rice surplus will continue to come from irrigated environments. In some major rice-producing countries, such as Bangladesh, the Philippines, and Thailand, there is still a large gap between actual and potential yields, and efforts need to be directed at crop management technologies to narrow the yield gap. In other countries, such as China, Japan, and the Republic of Korea, the yield gap is closing, and further yield increases can come only from increased genetic yield potential.

Increased yields and total production mean that, with current management practices, more water will be needed to meet increased transpiration requirements. With increasing water shortage, this means that the water productivity of rice needs to increase.

> The scope to increase the water productivity of rice through increased transpiration efficiency of the plant is small compared with decreased water losses from the field

Varietal improvement

Yield potential. The key attributes of the high-yielding varieties of the green revolution were semidwarf stature (which increased harvest index and lodging resistance) and photoperiod insensitivity. There are no indications that these factors can be further exploited to significantly increase the yield potential of inbred varieties under fully irrigated conditions (Peng and others 1999). For example, since the introduction of IR8 in the 1960s the yield potential of semidwarf tropical indica inbred varieties has stagnated at about 10 metric tons per hectare. Substantial yield improvement has recently come only from the development of hybrid rice, which has increased yield potential by 5%–15% over inbred varieties in the same environment. China's "super" rice–breeding program has developed several hybrid varieties with a yield of 12 metric tons per hectare in on-farm demonstration fields, which is 8%–15% higher than the hybrid check varieties. Transforming the C_3 rice plant into a C_4 plant through genetic engineering could be a long-term approach for increasing rice yield potential, but the feasibility and potential benefits of this approach are still being debated (Sheehy, Mitchell, and Hardy 2000).

Traditional breeding programs for irrigated environments have selected varieties under conditions of continuously ponded water. With increasing water scarcity in irrigated systems, breeding programs should include selection under conditions of water-saving technologies such as alternate wetting and drying or aerobic cultivation. Some success has been recorded with the development of high-yielding aerobic rice varieties in northern China, as discussed later (see section on "Tolerance to abiotic stresses").

Water productivity. The modern improved japonica varieties have a 25%–30% higher transpiration efficiency than the older indica varieties, suggesting considerable variation for this trait in rice germplasm (Peng and others 1998). The potential for exploiting this trait has not been investigated, however. Proposals to increase the waxiness of rice leaves to reduce nonstomatal transpiration have demonstrated no notable progress. Transforming the C_3 rice plant into a C_4 plant could potentially increase transpiration efficiency, but again, not much progress has been made.

Overall, the scope to increase the water productivity of rice through improved transpiration efficiency of the plant seems to be small compared with the scope to increase water productivity through reduced total water inputs (irrigation, rainfall). The shorter growth duration of modern high-yielding rice varieties has reduced outflows of evaporation, seepage, and percolation from individual rice fields. The combined effect of increased yield and reduced growth duration is that these varieties have a water productivity related to total inputs that is three times higher than that of traditional varieties grown under similar water management (Tuong and Bouman 2003). A range of breeding strategies can be explored to further increase water productivity through increased evapotranspiration efficiency, such as early vigor to reduce soil evaporation and weed suppression to reduce weed transpiration (Bennett 2003).

> **Other routes to increased yields and total production are through greater tolerance to abiotic stresses, including drought, submergence, and salinity**

Tolerance to abiotic stresses. Other routes to increased yields and total production are through greater tolerance to abiotic stresses, including drought, submergence, and salinity.

Drought. Most progress so far has come from the development of short-duration varieties that escape drought at the end of the rainy season (Bennett 2003). But during the last decade substantial genetic variability for grain yield under drought stress has been documented in both cultivated Asian rice, *Oryza sativa*, and its hardy African relative, *Oryza glaberrima*. New breeding approaches are resulting in the development of both upland and lowland rice varieties with improved tolerance to severe water stress during the sensitive stages of flowering and grain-filling, while retaining the ability to produce high yields when water supplies are not limiting. Two examples for upland environments are aerobic rice and Nerica (New Rice for Africa). Aerobic rice is higher yielding than traditional upland varieties and combines input responsiveness with improved lodging resistance and harvest index (Atlin and others 2006). These new varieties are designed for nonflooded, aerobic soil conditions in either rainfed or water-short irrigated environments. (Examples of adoption in Brazil and China are discussed later in the section on "Managing rice fields better.") Nerica is the result of crossing *Oryza glaberrima* with *Oryza sativa* species at the African Rice Centre (WARDA) beginning in the mid-1990s to combine the toughness of *glaberrima* with the productivity of *sativa* (Jones and others 1997). The aim was to combine resistance to local stresses with higher yield, shorter growth duration, and higher protein content than traditional rice varieties. The first Nerica series (1–18) were upland varieties; 8 varieties have been officially released. There are now 60 lowland Nerica varieties, 2 of which have been officially released in Burkina Faso and Mali.

Submergence. Though breeding for submergence tolerance and enhanced yield in flash-flood areas has been going on for more than three decades, only a few tolerant lines with improved agronomic characteristics have been developed so far. Recently, a few tolerant landraces were discovered that can withstand complete submergence for 10–14 days. New submergence-tolerant breeding lines with improved agronomic characteristics are now being developed by transferring this tolerance into semidwarf breeding lines using marker-assisted selection (box 14.6). Some breeding progress has been made for deepwater areas, and a few new lines with reasonable yield and grain quality have been released. Recently, three main quantitative trait loci (QTL; a region of DNA associated with a particular trait) were identified for elongation ability (Sripongpangkul and others 2000). Fine-mapping and tagging of these QTLs will facilitate their efficient incorporation into modern popular varieties through marker-assisted selection.

box **14.6** **Using molecular tools to accelerate breeding programs for desirable traits**

The complete sequencing of the rice genome is expected to accelerate the discovery and exploitation of useful genes in breeding programs. Molecular tools were used in the development of Nerica to overcome hybrid sterility, accelerating the breeding program from 5–7 years to about two years. For drought tolerance molecular tools are starting to identify genes controlling the responses of plants to water stress, but so far no quantitative trait loci (QTL) have been identified for tolerance to either reproductive- or vegetative-stage drought stress with effects large enough to be useful in breeding (Bennett 2003).

Molecular tools are contributing successfully to breeding for tolerance to salinity and submergence. An example is the recent advance in tolerance to flash flooding. Using a population developed from a cross between an indica submergence-tolerant line (IR40931) and a susceptible japonica line (PI543851) a major QTL was mapped to chromosome 9, designated as Sub1 (Mackill and Xu 1996). This QTL accounted for a large proportion of the phenotypic variation in submergence tolerance. The Sub1 QTL was fine mapped, and markers were developed and successfully used to transfer it into Swarna, a popular rainfed lowland variety sensitive to submergence, which became substantially tolerant to flooding under field conditions without changing its agronomic or quality traits. Efforts are ongoing to transfer the Sub1 QTL into other “Mega” varieties in rainfed lowlands such as BR11, IR64, Mahsuri, Samba Mahsuri, and CR1009.

Salinity. Despite a general sensitivity to salinity rice has considerable variation in tolerance. Combining new screening techniques with conventional, mutation, and anther culture techniques, salinity tolerance was successfully introduced into high-yielding plant types (Gregorio and others 2002). Some newly released varieties have demonstrated more than 50% yield advantage over current salt-sensitive varieties. Breeding cultivars with much higher tolerance is possible if component traits are combined in a suitable genetic background. The opportunity to improve salinity tolerance through the incorporation of useful genes or pyramiding of superior alleles appears very promising. A major QTL, designated Saltol, was recently mapped. It accounted for more than 70% of the variation in salt uptake in this population. Marker-assisted backcrossing is currently used to incorporate this QTL into popular high-yielding varieties.

To enhance adoption of improved varieties, farmers’ preferences need to be taken into account. This was done for the delivery of aerobic rice in Asia and Nerica in Africa through participatory varietal selection and community-based seed production systems.

Managing rice fields better

Irrigated environments. Increasingly, technologies that aim to close the gap between actual yields and potential yield need to apply holistic approaches that integrate crop, soil, and water management. An example is the system of rice intensification (Stoop, Uphoff, and Kassam 2002). As with all such approaches, care must be taken in promoting a single solution across environments, and site-specific adaptation must be allowed for. For example, the system of rice intensification in the original form developed in Madagascar has strict rules about the use of young seedlings, wide plant spacing, transplanting of single seedlings, transplanting in squares, alternate wetting and drying, manual or mechanic weeding, and large amounts of organic fertilizer. Though the validity of the principles behind the system are still questioned (Sheehy and others 2004; McDonald, Hobbs, and Riha 2006), many farmers pioneer the system in new areas by modifying it to suit their local needs and environments, often to the extent that the original approach is no longer recognizable.

Though water flows have hardly been studied in these integrated technologies, it is likely that yield increases are accompanied by relative increases in transpiration and by relative decreases in evaporation, seepage, and percolation. In terms of water savings any agronomic practice that increases the harvest index (ratio of crop yield to aboveground weight of the plant) will result in more grains per unit of water transpired and thus in increased water productivity.

Technologies that aim to close the gap between actual and potential yield need to apply holistic approaches that integrate crop, soil, and water management

Water-saving technologies. Various water-saving technologies exist or are being developed to help farmers cope with water scarcity in irrigated environments (Tuong, Bouman, and Mortimer 2005; Humphreys and others 2005). These technologies increase the productivity of water inputs (rainfall, irrigation) mainly by reducing unproductive seepage and percolation losses and to a lesser extent by reducing evaporation. Mechanical soil compaction can reduce percolation flows in certain soil types but may be too expensive for large-scale implementation and may adversely affect the growth of any upland crop following rice. General measures such as land leveling, farm channels, and good puddling and bund maintenance improve water control and reduce seepage and percolation outflows. Minimizing the turnaround time between wet land preparation and transplanting reduces the time when no crop is present and outflows of water from the field do not contribute to production.

Especially in large-scale irrigation systems with plot to plot irrigation the water losses during the turnaround time can be high when farmers maintain seedbeds in their main fields and keep the whole area flooded for the full duration of the seedbeds (Tabbal and others 2002). The losses can be minimized by installing field channels, adopting common seedbeds, or direct seeding. With field channels water can be delivered separately to individual seedbeds, and the main field does not need to be flooded. Common seedbeds, either communal or privately managed, can be located strategically close to irrigation canals and irrigated as one block. With direct seeding the crop starts growing and using water from the moment of establishment onwards. Direct dry seeding can also increase the effective use of rainfall and reduce irrigation needs (Cabangon, Tuong, and Abdullah 2002).

Water management techniques such as saturated soil culture and moderate alternate wetting and drying (without imposing drought stress) reduce field water application 15%–20% without significantly affecting yield and increase the productivity of total water input (Belder and others 2004; Tabbal and others 2002). For example, in experiments on alternate wetting and drying in China in a clay loam soil with shallow groundwater depths of 0–0.3 meters, alternate wetting and drying saved 10%–15% water with no effect on yield (table 14.2). More water can be saved and water productivity further increased by prolonging the periods of dry soil and imposing slight drought stress on the plants, but this usually comes at the expense of some loss of yield (Bouman and Tuong 2001). In experiments on alternate wetting and drying in the Philippines in a silty clay loam with table **14.2** **Yield and water use of alternate wetting and drying and aerobic rice systems, China, India, and the Philippines**

Country and source	**Year**	**Treatment**[a]	**Yield** (metric tons per hectare)	**Total water input**[b] (millimeters)	**Water productivity** (grams of grain per kilogram of water)
Philippines (Tabbal and others 2002)	1988	Flooded	5.0	2,197	0.23
		AWD	4.0	880	0.46
	1989	Flooded	5.8	1,679	0.35
		AWD	4.3	700	0.61
	1990	Flooded	5.3	2,028	0.26
		AWD	4.2	912	0.46
	1991	Flooded	4.9	3,504	0.14
		AWD	3.3	1,126	0.29
China (Belder and others 2004)	1999	Flooded	8.4	965	0.90
		AWD	8.0	878	0.95
	2000	Flooded	8.1	878	0.92
		AWD	8.4	802	1.07
India (Mishra and others 1990)	1983	Flooded	6.3	1,991	0.32
		AWD 1d	5.8	1,891	0.31
		AWD 3d	5.5	1,748	0.31
		AWD 5d	5.1	1,747	0.29
		AWD 7d	4.8	1,747	0.27
	1984	Flooded	6.3	1,890	0.33
		AWD 1d	5.9	1,569	0.38
		AWD 3d	5.6	1,426	0.39
		AWD 5d	5.1	1,352	0.38
		AWD 7d	5.0	1,352	0.38
Philippines (Bouman and others 2005)	2001	Flooded	5.1	1,718	0.29
		Aerobic	4.4	787	0.55
	2002	Flooded	7.3	1,268	0.58
		Aerobic	5.7	843	0.67
	2003	Flooded	6.8	1,484	0.46
		Aerobic	4.0	980	0.41
China (Yang and others 2005)	2001	Flooded	5.4	1,351	0.40
		Aerobic wet	4.7	644	0.73
		Aerobic dry	3.4	524	0.66
	2002	Flooded	5.3	1,255	0.42
		Aerobic wet	5.3	917	0.58
		Aerobic dry	4.6	695	0.66

a. AWD is alternate wetting and drying. In India the irrigation interval is given in days (d).

b. Rainfall plus irrigation, from crop establishment till harvest, excluding any contribution from groundwater.

groundwater depths of 0.7–2.0 meters water inputs in flooded rice were relatively high, and the alternate wetting and drying treatment saved more than 50% water with some 20% yield loss. In an experiment on clay loam in India, with a groundwater table fluctuating between 0.1 and 1.2 meters, increasing the number of days without ponded water progressively reduced both water inputs and yields.

Alternate wetting and drying reduce evaporation by 0%–30%, whereas the other water savings arise from reduced seepage and percolation loss (Belder and others 2005). The technique is a mature technology that has been widely adopted in China and can now be considered the common practice of lowland rice production in that country (Li and Barker 2004). It is also being recommended in northwestern India and parts of the Philippines.

In the system of *aerobic* rice specially adapted input-responsive rice varieties are grown under dryland conditions just like other cereals such as wheat, with or without supplemental irrigation (photo 14.5). In experiments in clay soil with groundwater at depths of 0.6–1.4 meters in the Philippines and in sandy soil with groundwater at 20 meters depth in northern China water inputs in aerobic rice systems were 30%–50% less than in flooded systems and yields were 20%–30% lower with a maximum of about 5.5 metric tons per hectare (see table 14.2). Reductions in evaporation losses were 50%–75%. Aerobic rice systems are currently being pioneered by farmers on an estimated 80,000 ha in north China (Wang and others 2002).

In the system of aerobic rice specially adapted input-responsive rice varieties are grown under dryland conditions just like other cereals

However, the development of aerobic rice systems for irrigated environments is in its infancy, and more research is needed to develop high-yielding varieties and sustainable management systems. In aerobic rice systems resource-conserving technologies, as practiced in upland nonrice crops, become available to rice farmers as well, such as mulching and zero or minimum tillage. Various methods of mulching are being experimented with in nonflooded rice systems in China and have been shown to reduce evaporation (Dittert and others 2002). Growing rice under aerobic conditions on raised beds shows promise but is also still in its infancy (Humphreys and others 2005).


Photo by Shaobing Peng

Photo 14.5

Sustainability and environmental protection. While more work has been done on the development of technologies to increase crop productivity under water scarcity, little attention has been paid to their long-term sustainability and environmental impacts. Studies are needed on the relationships between the use of organic and inorganic fertilizers and crop residue management on the one hand, and yield sustainability, greenhouse gas emissions, and pathways of nutrient losses on the other. The effectiveness and environmental impacts of fertilizer management technologies such as site-specific nutrient management, slow-release fertilizers, and deep placement need to be evaluated under various scenarios of water availability.

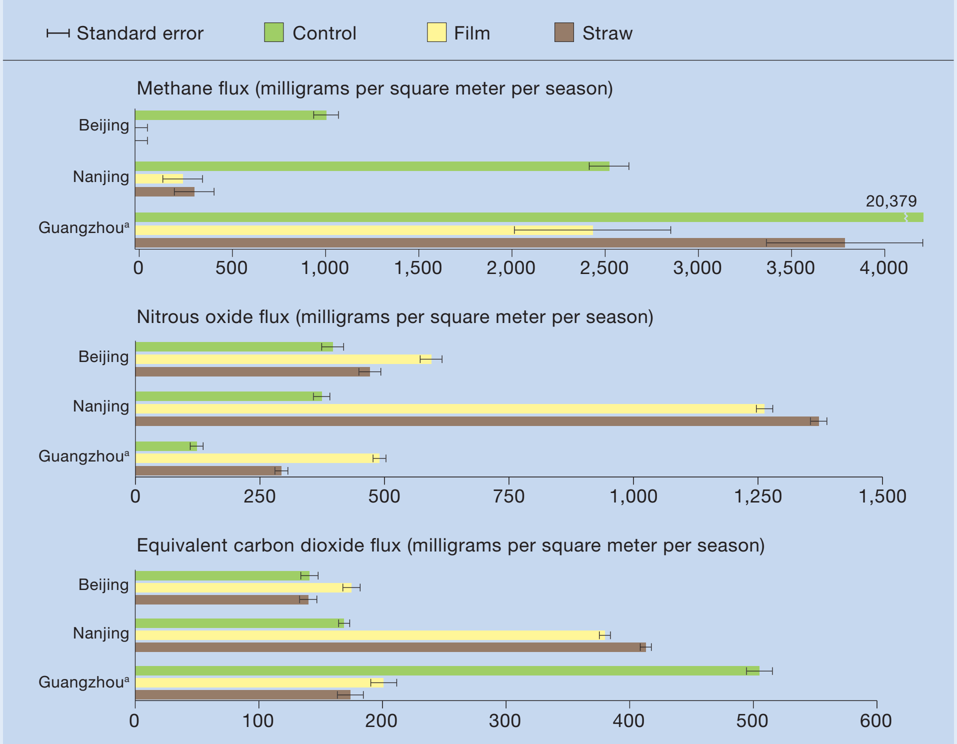
Water-saving technologies can have different effects on the emission of greenhouse gases, depending on environmental site conditions and management practices (box 14.7). With less water, weed management practices need to be developed that reduce the reliance on herbicides by anticipating weed species "shifts" and developing preventive strategies that integrate management interventions such as manual weeding, increased seed density (in direct-seeded systems), and mechanical weeding.

Little is known about changing pest and disease dynamics when field conditions change from water abundant to water short, although initial reports suggest an increase

box 14.7 Differences in greenhouse gas emissions under conventional and water-saving systems

The following figure shows the variability in greenhouse gas emissions from conventional flooded rice fields (control) and from two water-saving systems, unsaturated soil covered by plastic film (film) and unsaturated soil covered by straw mulch (straw) at three sites in China. Methane emission is highest from flooded rice at all three sites. Nitrous oxide emission is lowest from flooded rice at Nanjing and Guangzhou, but similar among all three systems at Beijing. When both methane and nitrous oxide emission are converted into equivalent carbon dioxide emission and summed, flooded rice has the lowest global warming potential at Nanjing and the highest global warming potential at Guangzhou, whereas all three systems had similar global warming potential at Beijing. The overall impact of the adoption of water-saving management practices in rice production on global warming is unknown and needs more study.

Variability in greenhouse gas emissions from conventional and water-saving systems 2002



Note: Results are the means of three replications on experimental fields. Carbon dioxide equivalents calculated using global warming potentials of methane and nitrous oxide based on a 100 year time horizon.

a. Only the late rice crop was evaluated.

Source: Dittert and others 2002.

in soil-borne pests such as nematodes. It is to be expected that under fully aerobic soil conditions rice cannot be grown continuously on the same piece of land each year (as can be successfully done with flooded rice) without yield decline (Peng and others 2006; Piñheiro and others 2006). Suitable crop rotation will be needed as well as varieties that are tolerant of soil-borne pests and diseases. The experiences of upland rice and other dryland crops with pest and disease management have to be exploited in the development of sustainable management systems for water-short irrigated environments. Under completely aerobic conditions salts may accumulate in the root zone as in any other dryland crop, and flooded rice could be included as a rotation crop to periodically flush down salts.

The high variability of rainfed environments exposes farmers to great risk of yield loss

Stress-prone environments. The high variability of rainfed environments exposes farmers to great risk of yield loss. The development of stress-tolerant and input-responsive varieties will reduce this risk and increase the incentive to use external inputs and intensify the cropping system. Adjusted cropping systems and management technologies will be needed to make the most efficient use of the possibilities offered by the new varieties. The combination of the improved rice varieties that are in the pipeline and specific management technologies has the potential to increase yields by 0.5–1.0 metric tons per hectare in environments prone to drought, flood, and salinity within the next 10 years.

Rainfed lowlands. Two promising technologies are direct seeding and improved nutrient management. Direct seeding potentially offers better use of early-season rainfall, better drought tolerance, lower risk from late season droughts, better use of indigenous soil nitrogen supply, and an increased possibility for a second crop. Site- and season-specific nutrient management can reduce nutrient losses and pollution of the environment. Both technologies have already enabled substantial productivity increases in some more favorable rainfed areas. In Lombok, Indonesia, the introduction of short-duration and input-responsive varieties with direct seeding and the use of inorganic fertilizer increased and stabilized yields (Fagi and Kartaatmadja 2002). In Lao PDR production in rainfed lowlands contributed considerably to achieving self-sufficiency in rice within a decade after the introduction of improved varieties and crop management (Pandey 2001).

Uplands. Strategies should aim at sustainable intensification to break the spiral of resource degradation caused by shorter fallow periods in shifting cultivation systems. For rice a promising option is the establishment of lowland fields in valley bottoms in mountainous areas, also referred to as “montane paddy rice” (Castella and Erout 2002). These lowland fields could benefit from irrigation water supplied by mountain streams that converge in the valley bottoms. Rainfed lowland rice fields are also found in shallow inland valleys in Sub-Saharan Africa, which have been identified as offering the greatest potential for expansion and intensification.

The aerobic rice production system offers scope where seasonal rainfall is some 600 mm or more or where farmers have access to supplementary irrigation. In the hilly regions of Yunnan Province in southern China farmers grow rainfed aerobic rice under intensified management, realizing yields of 3–4 metric tons per hectare (Atlin and others 2006). The combination of aerobic rice and terraces offers even greater scope for intensification. Aerobic rice also holds promise for permanent arable production systems in rotation with other crops. In Brazil a breeding program to improve upland rice has resulted in aerobic varieties with a yield potential of up to 6 metric tons per hectare (Piñheiro and others 2006). Farmers grow these varieties in rotation with crops such as soybean and fodder on large commercial farms with supplemental sprinkler irrigation on an estimated 250,000 ha of flatlands in the Cerrado region, realizing yields of 3–4 metric tons per hectare.

Submergence-prone environments. The new submergence-tolerant varieties need to be combined with adapted crop and nutrient management to improve seedling and plant survival as well as the ability to recover after submergence. Seedlings of submergence-tolerant varieties that are enriched in nutrients, particularly zinc and phosphorus, and possibly silicon, have a greater chance of survival. Application of nutrients after the recession of floodwater also speeds recovery, improves tillering, and boosts yield.

> Aerobic rice holds promise for permanent arable production systems in rotation with other crops

Salt- or sodic-affected areas. New salt-tolerant varieties need to be integrated with specific nursery, crop, and nutrient management strategies to mitigate the effects of salt stress and to improve soil quality. Soil amendments, particularly gypsum, can help in reclaiming sodic-affected soils, but they require large investments. The combined use of farmyard manure or pressmud from industrial waste with improved varieties can cut the need for gypsum by more than half. Relatively fresh irrigation water can leach salts accumulated in the root zone during previous nonrice crops.

Lowering the cost of production. There are many options to lower the costs of production, but few are directly related to water management. Where irrigation water is supplied by pumping, water-saving technologies reduce water inputs, pumping costs, and energy consumption. Whether this actually increases profitability depends on the yield obtained and the relative price of rice and water. Reducing irrigation frequency reduces the labor used for irrigation, but when fields are not continuously flooded, weed infestation may increase, requiring more labor or herbicides. The system of rice intensification has relatively high labor requirements and, partly as a result, there are reports of the system's abandonment in its country of origin, Madagascar (Moser and Barrett 2003). Dry seeding and aerobic rice technologies offer possibilities for mechanization of farm operations such as sowing, weed control, and combine harvesting, although adoption of these technologies seems to be driven more by labor shortage than by water shortage. Increased labor productivity also lowers the cost of production.

Options at the landscape level

Irrigation system efficiency and water reuse. Large volumes of water outflows through surface drainage, seepage, and percolation characterize irrigated rice fields. Although the outflows are losses from individual fields, there is great scope for reuse of these flows within a landscape that consists of many interconnected fields (figure 14.2). Surface drainage and seepage water usually flows into downstream fields and is lost only at the bottom of a toposequence when it flows into drains or ditches. Even then farmers can use small pumps to lift water from drains to irrigate fields that are inadequately serviced by irrigation canals. In many irrigation systems in low-lying deltas or flood plains with impeded drainage, the continuous percolation of water has created shallow groundwater tables close to the surface (Belder and others 2004;

Cabangon and others 2004). Again, farmers can either directly pump water from the shallow groundwater or pump groundwater when it becomes surface water as it flows into creeks or drains. Recent studies of rice-based irrigation systems in China indicate that irrigation efficiency improves with increasing spatial scale because of the reuse of water (Loeve and others 2004a; box 14.8). Much of this reuse is informal, as farmers take the initiative to pump up water, block drains, or construct small on-farm reservoirs for secondary storage.

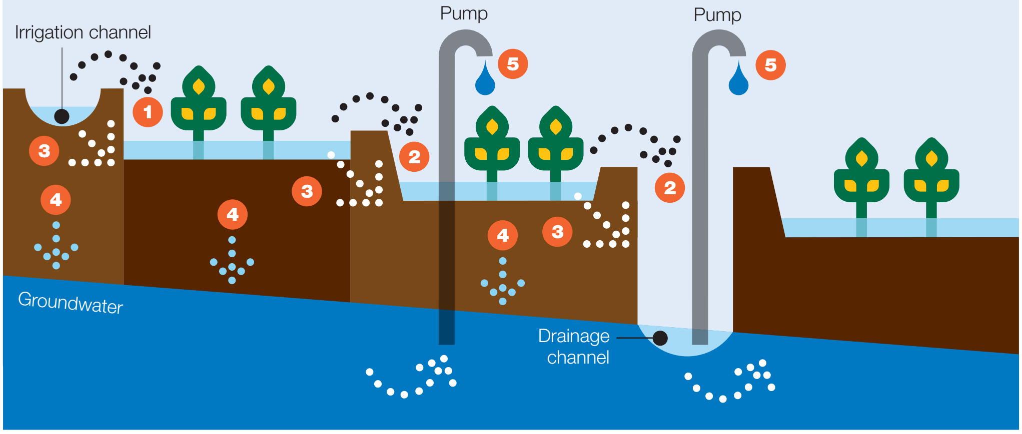
Although water can be efficiently reused this way, it does come at a cost and may not alleviate inequities among farmers in irrigation systems. The current debate on the improvement of irrigation systems focuses on the benefits and costs of system modernization relative to those of mostly informal reuse of water. System modernization aims to improve the irrigation system delivery infrastructure and operation scheme to supply each farmer with the right amount of water at the right time.

Stress-prone environments. There are many interventions at the landscape level that are effective in alleviating abiotic stresses. On-farm water harvesting can reduce drought risk and increase productivity in drought-prone rainfed environments by making small amounts of extra water available to bridge critical periods of dry spells. Developing reservoirs and canal networks to store rainwater or freshwater from rivers before it becomes

figure **14.2** **There is great scope for reuse of water flows in a rice landscape of interconnected fields**

Water flows

1 Water flows into the fields by irrigation
2 Water flows across fields by surface drainage
3 Water flows across fields by lateral seepage
4 Water recharges the groundwater through percolation
5 Water may be reused by pumping from ditches and from the groundwater that collects drainage, seepage, and percolation flows.



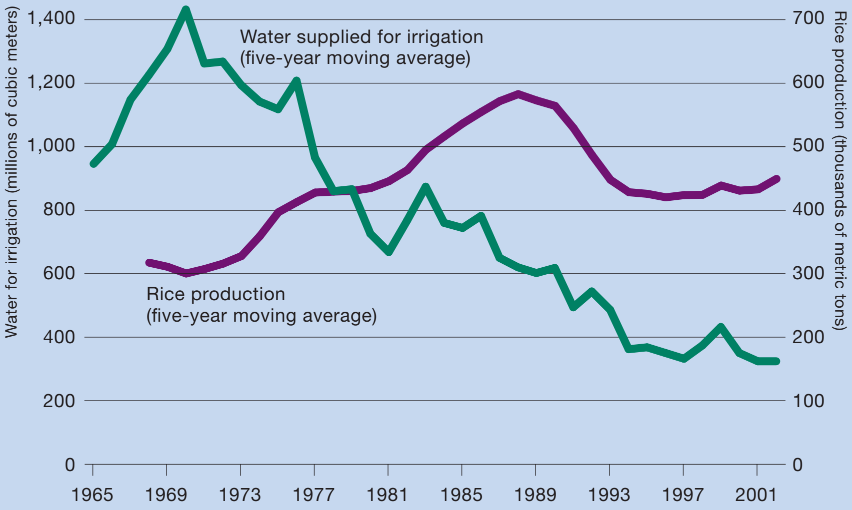
box **14.8** Producing more rice using less water

The Zanghe Irrigation System (ZIS) in the middle reaches of the Yangtze Basin has a command area of about 160,000 ha and services mainly rice in the summer season. Since the early 1970s the amount of water released to agriculture has been steadily reduced in favor of increased releases to cities, industry, and hydropower. By the mid-1990s the amount of water received by agriculture had declined to less than 30% of the amount received in the early 1970s. In the same period, however, rice production increased, peaking at about 650,000 metric tons in the late 1980s, or nearly twice the amount produced in the late 1960s (see figure). Although rice production has leveled off to a stable 500,000 metric tons in the last decade, more rice has been produced with less water over the past 30 years, thanks to a variety of integrated measures:

- Replacing double rice cropping by more water-efficient single rice cropping.
- Promoting alternate wetting-drying water-saving technology.
- Introducing volumetric water pricing and such institutional reforms as water user associations, which promote efficient use of water by farmers.
- Upgrading the irrigation system (for example, canal lining).
- Developing secondary storage through the creation of thousands of small- to large-size ponds and reservoirs.

The ZIS case study suggests that win-win situations are possible where rice production can be maintained, or even increased, while freeing up water for other purposes. A thorough understanding of the boundary conditions under which the ZIS success was accomplished may identify entry points for successful replication in other systems.

Water supply and rice production in the Zanghe Irrigation System in the Yangtze Basin



Source: Adapted from Loeve and others 2004b.

saline can extend the growing season in saline coastal areas and substantially improve productivity. Managing water by constructing large-scale coastal embankments and sluices has been reasonably successful in preventing seawater intrusion in many deltaic coastal areas, substantially reducing soil salinity in the wet season. The technology also opens up the possibility of growing high-yielding, modern rice varieties, as in the coastal areas of the Mekong Delta in Viet Nam (Tuong and others 2003).

However, water needs to be managed judiciously to avert undesirable long-term environmental consequences and local conflicts with other water users, especially landless poor people who depend on brackish water fisheries for their livelihood. The use of pumps for shallow groundwater (as in Bangladesh) or surface water (as in the Mekong Delta) allows cultivation of short-duration varieties in nonflooded periods in many deltas. Farmers in the flood-prone areas of the Mekong Delta also build community dikes, protecting areas of ten to a few hundred hectares and allowing them to harvest the crop before floods arrive. These dikes delay the onset of floods rather than prevent the peak of the flood from entering the protected area, thus avoiding the potentially adverse environmental consequences of absolute flood protection.

Water needs to be managed judiciously to avert undesirable long-term environmental consequences and local conflicts with other water users

Relationship between water use at field- and irrigation-system levels. The relationships between water use at the field- and irrigation-system level are complex and involve hydrologic, infrastructural, and economic aspects. At the field level farmers can increase water productivity and reduce water use by adopting water-saving technologies. For farmers who pay for the water they use, any savings in water translates directly into a reduction in costs, thus increasing the profitability of rice farming.

At the irrigation-system level the adoption of field-level water-saving technologies by farmers will reduce the amount of evaporative losses from rice fields, but by relatively small amounts (see section on “Water-saving technologies”). The biggest water savings at the field level come from reducing seepage, percolation, and surface drainage flows. But while this retains more water at the surface (in the irrigation canals), which is available for downstream farmers, it reduces the amount of water re-entering the hydrological cycle and thus reduces options for informal reuse downstream. Reducing percolation from rice fields can lower groundwater tables. While deeper groundwater tables can adversely affect yields, because rice plants may be less able to extract water from the groundwater (Belder and others 2004), and increase the cost of pumping for reuse downstream, deeper groundwater tables also reduce nonproductive evaporation flows from fallow land.

Any adoption of water-saving technologies requires considerable water control by the farmer. This is not much of a problem for farmers using their own pumps, but can be a problem for farmers in large-scale, unreliable surface irrigation systems that lack flexibility in water delivery and for farmers using electric pumps for groundwater in areas where electricity supply is unreliable. For farmers to profit from water-saving technologies, irrigation systems need to be modernized, which has an economic cost. Integrated approaches that take into account the options for reuse of water and for conjunctive use of surface water and groundwater seem to be the best way forward to improve total water use efficiency at the system scale (see box 14.8).

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