4 Rice Production in Water-scarce Environments

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Abstract

Rice production in Asia needs to increase to feed a growing population. Though a complete assessment of the level of water scarcity in Asian rice production is still lacking, there are signs that declining quality of water and declining availability of water resources are threatening the sustainability of the irrigated rice-based production system. Drought is one of the main constraints for high yield in rain-fed rice. Exploring ways to produce more rice with less water is essential for food security and sustaining environmental health in Asia. This chapter reviews the International Rice Research Institute (IRRI)'s integrated approach, using genetics, breeding and integrated resource management to increase rice yield and to reduce water demand for rice production. Water-saving irrigation, such as saturated-soil culture and alternate wetting and drying, can drastically cut down the unproductive water outflows and increase water productivity. However, these technologies mostly lead to some yield decline in the current lowland rice varieties. Other new approaches are being researched to increase water productivity without sacrifice in yield. These include the incorporation of the C_4 photosynthetic pathway into rice to increase rice yield per unit water transpired, the use of molecular biotechnology to enhance drought-stress tolerance and the development of 'aerobic rice', to achieve high and sustainable yields in non-flooded soil. Through the adoption of water-saving irrigation technologies, rice land will shift away from being continuously anaerobic to being partly or even completely aerobic. These shifts will have profound changes in water conservation, soil organic-matter turnover, nutrient dynamics, carbon sequestration, soil productivity, weed ecology and greenhouse-gas emissions. Whereas some of these changes can be perceived as positive, e.g. water conservation and decreased methane emission, some are perceived as negative, e.g. release of nitrous oxide from the soil and decline in soil organic matter. The challenge will be to develop effective integrated natural-resource-management interventions, which allow profitable rice cultivation with increased soil aeration, while maintaining the productivity, environmental services and sustainability of rice-based ecosystems.

Introduction

The past years have seen a growing scarcity of water worldwide. The pressure to reduce water use in irrigated agriculture is mounting, especially in Asia, where it accounts for 90% of total diverted fresh water. Rice is an obvious target for water conservation: it is grown on more than 30% of irrigated land and accounts for 50% of irrigation water (Barker *et al.*, 1999). Reducing water input in rice production can have a high societal and

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environmental impact if the water saved can be diverted to areas where competition is high. A reduction of 10% in water used in irrigated rice would free 150,000 million m^3, corresponding to about 25% of the total fresh water used globally for non-agricultural purposes (Klemm, 1999). However, rice is very sensitive to water stress. Attempts to reduce water in rice production may result in yield reduction and may threaten food security in Asia. Reducing water input for rice will change the soil from submergence to greater aeration. These shifts may have profound – and largely unknown – effects on the sustainability of the lowland rice ecosystem. Our challenge is to develop socially acceptable, economically viable and environmentally sustainable novel rice-based systems that allow rice production to be maintained or increased in the face of declining water availability. This chapter reviews the status of water resources in rice-growing areas and the opportunities and challenges of growing more rice with less water.

Water Resources in Rice-growing Areas

Rice can be grown under irrigated (lowland) or rain-fed (upland or lowland) conditions. Rain-fed rice occupies about 45% of the global rice area and accounts for about 25% of the rice production. Drought has been identified as one of the main constraints for improving yield, which currently averages 2.3 t ha^{-1}. According to Garrity *et al.* (1986), 50% of rain-fed lowland and all rain-fed uplands are drought-prone. Severe and mild droughts often occur in predominantly rain-fed rice areas, such as north-east Thailand, Laos, central Myanmar and east and north-east India (Plate 1).

More than 75% of the rice supply comes from 79 million ha of irrigated lowlands. Rice production in the subtropical regions of north and central China, Pakistan and north-west India mostly depends on wet-season (summer) rainfall, with supplementary irrigation (Plate 2a). Dry-season irrigated rice is concentrated in south China, south and east India and the whole of South-East Asia (Plate 2b). In-depth assessment of the availability of irrigation water in the irrigated rice area is lacking. By overlaying the International Water Management Institute (IWMI)'s water-scarcity atlas (IWMI, 2000) with the International Rice Research Institute (IRRI)'s rice-area maps, it is expected that wet-season irrigated rice areas in north China (2.5 million ha), Pakistan (2.1 million ha) and north and central India (8.4 million ha) will experience 'physical water scarcity' by 2025 (Plate 2a). In addition, about 2 million ha of the dry-season irrigated rice in central India (Plate 2b) will suffer physical scarcity. Most of the approximately 22 million ha dry-season irrigated rice areas in south and South-East Asia fall in the 'economic water scarcity' zone. However, there may be an overestimation of the water availability in the dry season because IWMI's water-scarcity calculations are based on the annual water balance. In principle, water is always scarce in the dry season, when the lack of rainfall makes cropping impossible without irrigation. Thus, there may be rice areas in the 'economic water scarcity' zone affected by 'physical water scarcity' in the dry season.

There is evidence that water scarcity already prevails in rice-growing areas (Plate 3). Consequent overexploitation of groundwater in the last decades has caused serious problems in China and south Asia (Postel, 1997; Sha *et al.*, 2000; Shu Geng *et al.*, 2001). Groundwater tables have dropped, on average, by 1–3 m $year^{-1}$ in the North China Plain, by 0.5–0.7 m $year^{-1}$ in the Indian states of Punjab, Haryana, Rajasthan, Maharashtra, Karnataka and northern Gujarat and by about 1 m $year^{-1}$ in Tamil Nadu and hard-rock southern India. This has led to increased costs of pumping, salinity intrusion, fluoride contamination, land subsidence and the formation of cracks and sink holes (North China Plain). These major groundwater-depletion areas affect rice production in the rice–wheat-growing areas in northern India, Pakistan and China and in the rice-growing areas in Tamil Nadu. In the Ganges delta of Bangladesh, overdrawing of groundwater in the dry season leads to wells falling dry in rice-producing areas, but water levels are restored during the wet season. A specific problem attributed to falling groundwater tables here (and in parts of eastern India) is the appearance of poisonous arsenic.

Heavy upstream water use along some major rivers in Asia is causing severe water shortages downstream. China's Yellow River, which flows for 4600 km through some of Asia's richest farmland, has run dry nearly every year since 1972 (Postel, 1997; Shu Geng *et al.*, 2001). Such is the demand on its water that, in 1997, its final 600 km were dry for more than 4 months. The government of China has prohibited flooded rice cultivation around Beijing (Wang Huaqi *et al.*, 2003). In south Asia, the Ganges and Indus Rivers have little to no outflow to the sea in the dry season. Less dramatic, but more important for rice-growing areas, is the fact that heavy competition for river water between states and different sectors (city, industry) is causing water scarcity for agriculture in southern India's Cauvary delta and in Thailand's Chao Phraya delta (Postel, 1997).

Irrigated rice production is also increasingly facing competition from other sectors. The irrigated rice area in China was reduced by 4 million ha between the 1970s and the 1990s (Barker *et al.*, 1999). Though it is not possible to claim that this reduction in irrigated rice area is entirely due to water scarcity, there is evidence that the reduced area is related to the reduction in the amount of water that is diverted to irrigate rice land. For example, in the 160,000 ha Zhanghe irrigation system (Hubei Province, China), the share of water allocated for irrigation was dominant (about 80%) until the 1980s. Afterwards, Zhanghe reservoir water was increasingly used to meet the growing demand for water by cities and industry and for hydropower generation, and the amount of water allocated for irrigation declined to about 20% in the late 1990s. The irrigated rice area in the 1990s was reduced by about 20% from the level in the 1980s (Fig. 4.1). As a consequence, rice production was also reduced (Dong Bin *et al.*, 2001). Similar examples of increased competition exist elsewhere in Asia. Water from the Angat reservoir in Bulacan Province, the Philippines, is increasingly diverted towards Manila at the expense of downstream water availability for agriculture (Bhuiyan and Tabbal, as cited in Pingali *et al.*, 1997, pp. 196–197). In other areas, water availability is threatened by degrading water quality caused by industrial pollution. Water in the Agno River in the Pangasinan Province is polluted with sediments and chemicals from mining activities upstream (Castañeda and Bhuiyan, 1993). Postel (1997) listed examples of competition between industrial and agricultural uses of water in India.

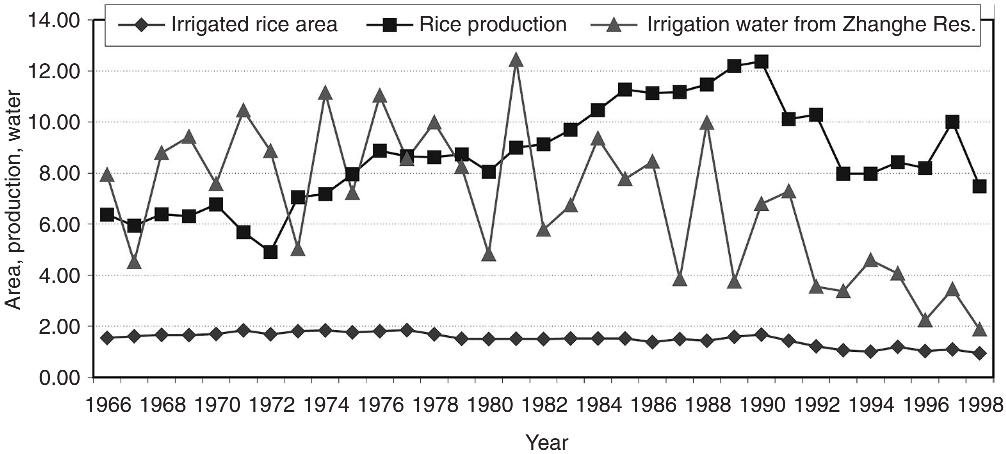

Fig. 4.1. Irrigated rice area (10^5 ha), rice production (10^8 kg) and irrigation water (10^8 m^3) from reservoir (1966–1998), Zhanghe irrigation system, Hubei province, China (from Dong Bin *et al.*, 2001).

Water Productivity in Rice

Rice and water input

Lowland rice in Asia is mostly transplanted or direct (wet)-seeded into puddled, lowland paddy-fields. Land preparation of a paddy consists of soaking, ploughing and puddling. Puddling is mainly done for weed control but it also increases water retention, reduces soil permeability and eases field levelling and transplanting (De Datta, 1981). Soaking is a one-time operation and requires water to bring the topsoil to saturation and to create a ponded water layer. There are often 'idle periods' in between tillage operations and transplanting, prolonging the land preparation period up to 1–2 months in large-scale irrigation systems (Tuong, 1999). The crop growth period runs from transplanting to harvest. During this period, fields are flooded with typically 5–10 cm of water until the final drainage some 10 days before the harvest.

Under flooded conditions, water is required to match outflows (seepage (S) and percolation (P)) to the surroundings and depletions to the atmosphere (evaporation (E) and transpiration (T)). The flow rates of S and P are governed by the water-head (depth of ponded water) on the field and the resistance to water movement in the soil. Because they are difficult to separate in the field, S and P are often taken together as one term, i.e. SP. SP can be as high as 25 mm day^{-1} during land preparation, because soil cracks do not close completely during land soaking (Tuong *et al.*, 1996). Typical SP rates for paddy-fields during the crop growth period vary from 1–5 mm day^{-1} in heavy clay soils to 25–30 mm day^{-1} in sandy and sandy loam soils (Wickham and Singh, 1978; Jha *et al.*, 1981). Only E (from ponded water or moist soil) takes place during land preparation, whereas both E (from soil and water surface between crops) and T occur during the crop growth period. Since it is difficult to separate E and T during crop growth, they are often expressed in one term, evapotranspiration (ET). Typical ET rates of rice in Asia range from 4 to 7 mm day^{-1} (De Datta, 1981; Tuong, 1999).

The water input in paddy-fields depends on the rates of the outflow processes and on the duration of land preparation and crop growth. For a typical 100-day season of modern high-yielding rice, the total water input varies from 700 to 5300 mm, depending on climate, soil characteristics and hydrological conditions (Table 4.1), with 1000–2000 mm as a typical value for many lowland areas. Of all outflows of water from a paddy-field,

Table 4.1. Typical daily rates of water outflows and seasonal water input in lowland rice production in the tropics.

	Daily (mm day^{-1})	Duration (days)	Season (mm)
Land preparation			
Land soaking			100–500
Evaporation	4–6	7–30	28–180
Seepage and percolation	5–30	7–30	35–900
Total land preparation			160–1580
Crop growth period			
Evapotranspiration			
Wet season	4–5	100	400–500
Dry season	6–7	100	600–700
Seepage and percolation			
Heavy clays	1–5	100	100–500
Loamy/sandy soils	15–30	100	1500–3000
Total crop growth			500–3700
Total seasonal water input			660–5280
Typical range of values for total seasonal water input			1000–2000

only T is 'productive' water use, since it leads directly to crop growth and yield formation. Most of the water input to a ricefield, however, is to compensate for E during land preparation and SP during land preparation and the crop growth period. These flows are unproductive as they do not contribute to crop growth and yield formation.

Water productivity

Water productivity is the amount of grain yield obtained per unit water. Depending on the type of water flows considered, water productivity can be defined as grain yield per unit water evapotranspired (WP_{ET}) or grain yield per unit total water input (irrigation plus rainfall) (WP_{IP}). At the field level, WP_{ET} values under typical lowland conditions range from 0.4 to 1.6 g kg^{-1} and WP_{IP} values from 0.20 to 1.1 g kg^{-1} (Tuong, 1999; Bouman and Tuong, 2001). The wide range of WP_{ET} reflects the large variation in rice yield as well as in ET caused by differences in environmental conditions under which rice is grown. Compared with other C_3-type food crops, such as wheat, rice has only slightly lower WP_{ET} values (Table 4.2). However, the WP_{IP} of rice is somewhat less than half that of wheat. The relatively low WP_{IP} of rice is largely due to the high unproductive outflows discussed above (SP and E).

Besides the yield and the size of field-level water outflows, the scale and the boundary of the area over which water productivity is calculated greatly affect its value. This is because the outflow 'losses' by S, P and runoff at a specific location (or field) can be reused at another location within the area under consideration. Data on water productivity across scales are useful parameters to assess whether water outflows upstream are effectively reused downstream. So far, we have found only a few reliable data on the water productivity at different scale levels within irrigation systems (Table 4.3). These limited data suggest that water productivities at scale levels larger than the field level vary widely and are within the variation of water productivities at the field level. The paucity of data on water productivity at scale levels higher than the field level reflects the lack of: (i) data on water flows or yield or both at such scales; and (ii) cooperation between those who work in agriculture (who

Table 4.2. Water productivity of rice, wheat and maize in terms of grain yield (g) per kg of water evapotranspired (WP_{ET}) and per kg of total water (rainfall plus irrigation) input (WP_{IP}) (adapted from Tuong, 1999).

WP_{ET}	WP_{IP}	Source of data used in calculating water productivity	Location
Rice			
	0.05–0.25	Bhatti and Kijne (1992), rainwater not included	Pakistan
1.39–1.61	0.29–0.39	Bhuiyan *et al.* (1995), wet-seeded rice	Philippines
1.1		Sandhu *et al.* (1980)	India
0.88–0.95	0.33–0.58	Kitamura (1990), dry season	Malaysia
0.89		Mishra *et al.* (1990)	India
0.4–0.5		Khepar *et al.* (1997)	India
	0.2–0.4	Bouman and Tuong (2001); 24 data sets	India
	0.3–1.1	Bouman and Tuong (2001); 16 data sets	Philippines
Wheat			
1.0–2.0		Turner (1997)	Australia
1.0–1.5	1.0–1.6	Deju and Lu Jingwen (1993), winter wheat	China
0.65	0.8	Sharma *et al.* (1990)	India
0.87	0.79	Pinter *et al.* (1990)	
Maize			
2.8	2.2–3.9	Stegman (1982)	USA
1.9–2.8	1.9–2.5	Moridis and Alagcan (1992)	Philippines
1.7–2.1	1.6–1.7	Stockle *et al.* (1990)	USA

Table 4.3. Water productivity (g rice kg^{-1} water) in respect of evapotranspiration (WP_{ET}), irrigation (WP_I) and total water input (WP_{IP}) at different scales.

Area (ha)	WP_{ET}	WP_I	WP_{IP}	Location	Source
30–50	0.5–0.6	1–1.5	0.25–0.27	Muda irrigation system, Kendal, Malaysia	Cabangon *et al.* (2002)
287–606	1–1.7	0.4–1	–	Zhanghe irrigation system, Hunan, China	Dong Bin *et al.* (2001)
Over 10^5	–	1–2.5	0.5–1.3		

may have production data) and those who work in the water-management sector (who may have water-flow data).

Strategies for Increasing Water Productivity at the Field Level

Increasing water productivity at the field level can be accomplished by: (i) increasing the yield per unit cumulative ET; (ii) reducing the unproductive water outflows and depletions (SP, E); or (iii) making more effective use of rainfall. The last strategy is important from the economic and environmental points of view, where the water that needs to be provided through irrigation can be offset by that supplied or replaced entirely by rainfall.

Increasing yield per unit ET: germplasm development and agronomic practices

Germplasm development has played an important role in increasing water productivity in rice production. By increasing yield and simultaneously reducing crop duration (and therefore the outflows of ET, S and P), the modern 'IRRI varieties' have about a threefold increase in water productivity compared with the traditional varieties. Most of the increase in WP_{ET}, however, occurred in cultivars released before 1980 (Tuong, 1999). This is because the increase in yield from 1966 to the early 1980s is coupled with a decrease in growth duration, whereas cultivars released after the mid-1980s have a longer duration than those released before 1980 (Peng *et al.*, 1998). Advancement in the development of tropical japonicas (also called the 'new plant type' (IRRI, 1998)) and hybrid rice will enhance water productivity. Peng *et al.* (1998) reported that the ratio of photosynthesis to T was 25–30% higher for the tropical japonica than for the indica type.

In the low-fertility, drought-prone rainfed environments, breeders have been most successful in manipulating drought escape. Exposure to drought is minimized by reducing crop duration or by minimizing the risk of coincidence of sensitive crop stages with water-deficit periods. The progress in breeding for drought tolerance is less spectacular, and the difficulties encountered are often blamed on the genetic complexity of the trait and its interaction with the environment. Nevertheless, drought-resistant varieties are being bred and released in upland and drought-prone rain-fed lowland areas. Salinity-tolerant varieties, such as Ir51500-AC11–1, allow us to grow rice in areas where salinity problems exclude the cultivation of conventional lowland varieties.

Improved agronomic practices, such as site-specific nutrient management, good weed management and proper land levelling, can increase rice yield significantly without affecting ET and, therefore, may result in increased water productivity (Moody, 1993; Tuong *et al.*, 2000; Hill *et al.*, 2001).

Reducing unproductive water outflows

Large reductions in water input can be potentially realized by reducing the unproductive E and SP flows during land preparation and during the crop growth period (Tuong, 1999; Bouman and Tuong, 2001). There are basically three ways to do so: (i) minimizing the idle periods during land preparation; (ii) increasing the resistance to water flow in the soil; and (iii) decreasing the hydrostatic water pressure.

Minimizing idle periods during land preparation

In transplanted rice, seedlings are usually nurtured in a seedbed for about 2–4 weeks. In irrigation systems that lack tertiary and field channels and with field-to-field irrigation, all the fields surrounding the seedbeds are being tilled (land preparation) and flooded during this period. This land-preparation period can be shortened by the provision of tertiary infrastructure to: (i) supply irrigation water directly to the nurseries without having to submerge the main fields; and (ii) allow farmers to carry out their farming activities independently of the surrounding fields (Tuong, 1999). In the Muda irrigation scheme, Malaysia, increasing the canal and drainage intensity from 10 to 30 m ha^{-1} has enabled farmers to shorten their land preparation by 25 days, resulting in annual water savings of 375 mm in two rice cropping seasons (Abdullah, 1998). In some countries, such as Vietnam and China, specific land areas are set aside for community seedbeds, which can be irrigated independently.

Another way to reduce the idle period during land preparation in irrigation systems without tertiary canals is the use of direct seeding (Bhuiyan *et al.*, 1995). However, the crop growth period in the main field of transplanted rice is shorter than that of direct-seeded rice. Thus, the amount of water saved by direct seeding depends on the balance between the reduction in water use caused by shortened land preparation and the increase in water use caused by prolonged crop growth duration in the main field (after crop establishment (Cabangon *et al.*, 2002)).

Soil management to increase resistance to water flow

The resistance to water flow can be increased by changing the soil physical properties. Cabangon and Tuong (2000) showed the beneficial effects of an additional shallow soil tillage before land preparation to close cracks that cause rapid bypass flow at land soaking. Thorough puddling results in a good compacted plough soil that impedes vertical water flow (De Datta, 1981). Soil compaction using heavy machinery has been shown to decrease soil permeability in north-east Thailand in sandy and loamy soils with at least 5% clay (Sharma *et al.*, 1995). Researchers have even experimented with introducing physical barriers underneath paddy soils, such as bitumen layers and plastic sheets (Garrity *et al.*, 1992). However effective, though, soil compaction and physical barriers are expensive and beyond the financial scope of most farmers.

Water management to reduce hydrostatic pressure

Reducing S and P flows through reduced hydrostatic pressure can be achieved by changed water management (Bouman *et al.*, 1994). Instead of keeping the rice-field continuously flooded with 5–10 cm of water, the floodwater depth can be decreased, the soil can be kept around saturation (saturated soil culture (SSC)) or alternate wetting and drying (AWD) regimes can be imposed. Soil saturation is mostly achieved by irrigating to about 1 cm water depth a day or so after disappearance of standing water. In AWD, irrigation water is applied to obtain 2–5 cm floodwater depth after a larger number of days (ranging from 2 to 7) have passed since the disappearance of ponded water. Wei Zhang and Si-tu Song (1989) reported yield increase under AWD. Our recent work indicates, however, that these are the exception rather than the rule (Bouman and Tuong, 2001; Tabbal *et al.*, 2002b). In most cases, SSC and AWD decrease yield. The level of yield decrease depends largely on the ground water-table depth, the evaporative demand and the drying period in between irrigation events (in the case of AWD). Mostly, however, relative reductions in water input are larger than relative losses in yield, and therefore water productivities in respect of total water input increase (Fig. 4.2). In some cases, AWD even doubled the water productivity compared with conventional flooded irrigation, but with yield reductions up to 30% (e.g. Tabbal *et al.*, 1992).

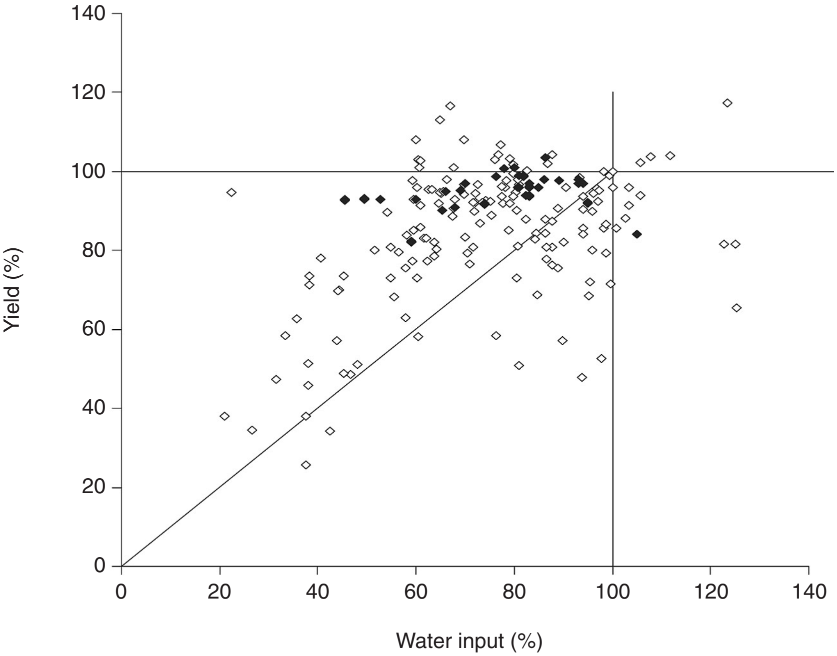

Fig. 4.2. Relative yield versus relative water input. The ◆ markers are data from SSC treatments or having only 1 day no standing water between irrigation turns (*N* = 31); the ◇ markers are from AWD treatments (*N* = 149). Relative yield is calculated as yield in the water-saving treatment over yield of control treatment with ponded water. Relative water input is calculated as the total water input (irrigation plus rainfall) in the water-saving treatment over that in the control treatment. (From Bouman and Tuong, 2001.)

Using Rainfall More Effectively

Dry-seeded rice technology offers a significant opportunity for conserving irrigation water by using rainfall more effectively. In transplanted and wet-seeded rice systems, farmers normally wait for delivery of canal water before they start land soaking. In dry-seeded rice, land preparation is done with dry or moist soil conditions and is started using early monsoonal rainfall. Crop emergence and early growth also occur in the early part of the monsoon, and only later, when canal water is available, is the crop irrigated as needed. Tabbal *et al.* (2002a) demonstrated the feasibility of dry-seeded rice in wet-season irrigated areas in the Philippines. Cabangon *et al.* (2002) reported that dry-seeded rice significantly increased water productivity in respect of irrigation water over wet-seeded and transplanted rice in the Muda irrigation scheme, Malaysia (Table 4.4). However, it was also observed that all three crop-establishment practices had similar total water input and water productivity in respect of total water input. An additional advantage of dry seeding is the early establishment of the crop, which may allow farmers to grow an extra crop after harvest on residual soil moisture (My *et al.*, 1995; Saleh and Bhuiyan, 1995) or using saved irrigation water. In purely rain-fed systems, early establishment and harvest of dry-seeded rice allows the rice plants to escape any late-season drought and hence improve the yield and its reliability.

Emerging Approaches

Raised beds for saturated soil culture

Implementing SSC requires good water control at the field level, and frequent turns of shallow irrigation, which are labour-intensive. Borell *et al.* (1997) experimented with raised

Table 4.4. Mean ± SE of grain yield (t ha^{-1}) and water productivity (g rice kg^{-1} water) in respect of irrigation (WP_I), to total water input (WP_{I+R}), to evapotranspiration from rice area + evaporation from non-rice area (WP_{ET+E}) and to evapotranspiration from rice area (WP_{ET}), in dry-seeded (DS), wet-seeded (WS) and transplanted (TP) irrigation service units (ISU) (from Cabangon *et al.*, 2002).

Parameter	DS ISU	WS ISU	TP ISU
Yield	$4.14 \pm 0.17^{b*}$	$4.50 \pm 0.23^{a, b}$	4.79 ± 0.23^{a}
WP_I	1.48 ± 0.26^{a}	0.62 ± 0.30^{b}	1.00 ± 0.30^{b}
WP_{I+R}	0.27 ± 0.02^{a}	0.26 ± 0.02^{a}	0.25 ± 0.02^{a}
WP_{ET+E}	0.38 ± 0.02^{a}	0.42 ± 0.02^{a}	0.39 ± 0.02^{a}
WP_{ET}	0.48 ± 0.03^{b}	0.53 ± 0.04^{b}	0.61 ± 0.04^{a}

*In a row, mean ± SE followed by the same letter are not significantly different at the 5% level by least significant difference.
SE, standard error.

beds in Australia to facilitate SSC practices. Water in the furrows (30 cm width and 15 cm depth) kept the beds (120 cm wide) at saturation. Compared with flooded rice, water savings were 34% and yield losses 16–34%. Thompson (1999) found that SSC in southern New South Wales, Australia, reduced both irrigation-water input and yield by a bit more than 10%, thus maintaining the irrigation-water productivity. Yield decline due to cold damage is likely for current varieties grown using SSC in that environment. Borell *et al.* (1997) pointed out the need for further research to determine which components of the water balance were responsible for the differences in total water use.

The benefits of growing rice on raised beds with SSC may be extended to a post-rice crop, such as wheat in the rice–wheat system. The productivity of crops sown after rice is often low due to poor soil physical structure and waterlogging from winter rainfall and spring irrigation. A bed system may improve drainage conditions for a post-rice crop.

Aerobic rice

A fundamental approach to reducing water inputs in rice is to grow the crop like an irrigated upland crop, such as wheat or maize. Instead of trying to reduce water input in lowland paddy-fields, the concept of having the field flooded or saturated is abandoned altogether. Upland crops are grown in non-puddled, aerobic soil without standing water. Irrigation is applied to bring the soil water content in the root zone up to field capacity after it has reached a certain lower threshold. The amount of irrigation water should match E from the soil and T by the crop (plus any application inefficiency losses). The potential water savings when rice can be grown as an upland crop are large, especially on soils with high SP rates (Bouman, 2001). Besides cutting down on SP losses, E is also reduced, since there is no standing-water layer.

De Datta *et al.* (1973) experimented with the cultivation of a high-yielding lowland rice variety (IR20) like an upland crop under furrow irrigation. Total water savings were 56% and irrigation water savings 78% compared with growing the crop under flooded conditions. However, the yield was reduced from 7.9 t ha^{-1} to 3.4 t ha^{-1}. Studies on non-flooded irrigated rice using sprinkler irrigation were conducted in Louisiana and Texas, USA (Westcott and Vines, 1986; McCauley, 1990). The experiments used commercial lowland rice cultivars. Irrigation water requirements were 20–50% less than in flooded conditions, depending on soil type, rainfall and water management. The highest-yielding cultivars (producing 7–8 t ha^{-1} under flooded conditions), however, had yield reductions of 20–30% compared with flooded conditions. The most drought-resistant cultivars produced the same under both conditions, but yield levels were much lower (5–6 t ha^{-1}).

New varieties must be developed if the concept of growing rice like an irrigated upland crop is to be successful. Upland rice varieties exist, but have been developed to give stable though low yields in adverse environments where rainfall is low, irrigation is absent, soils are poor or toxic, weed pressure is high and farmers are too poor to supply high inputs. IRRI recently coined the term 'aerobic rice' to refer to high-yielding rice grown in non-puddled, aerobic soil (Bouman, 2001). Aerobic rice has to combine characteristics of both the upland and the high-yielding lowland varieties. Evidence for its feasibility comes from Brazil and northern China. In Brazil, aerobic rice cultivars have come out of a 20-year breeding programme to improve upland rice with yields of 5–7 t ha^{-1} under sprinkler irrigation in farmers' fields (Silveira Pinheiro and Maia de Castro, Los Baños, Philippines, September 2000, personal communication). These varieties are grown commercially on 250,000 ha in the state of Mato Grosso. In north China, aerobic rice cultivars called Han Dao have been developed that yield up to 6–7.5 t ha^{-1} under flash irrigation in bunded fields (Wang Huaqi *et al.*, 2003). In a recent study of farmers testing aerobic rice in north China, it was found that yields of 4.6–6.6 t ha^{-1} were obtained with as little as 476–612 mm of total water input on loamy soils (Bouman *et al.*, 2002). It is estimated that Han Dao varieties are now being pioneered on some 120,000 ha in the North China Plains.

Biotechnology

The recent advances in genomics, the development of advanced analytical tools at the molecular level and genetic engineering provide new avenues for raising the yield potential and enhancing drought-stress tolerance. For example, the incorporation of the C_4 photosynthetic pathway into rice (being a C_3 plant), if achieved, can potentially increase water productivity by 80% (J.E. Sheehy, personal communication). Table 4.2 also indicates that water productivity of maize (a C_4 crop) is significantly higher than that of rice and wheat (C_3 crops).

The currently slow progress in breeding for drought tolerance may be accelerated by the discovery and subsequent manipulation of regulatory genes underlying the complex physiological and biochemical responses of rice plants to water deficit. Common research tools, tolerance mechanisms and breeding solutions are emerging across the evolutionary diversity of crops and plants. The enormous public- and private-sector investments in genomic analysis of *Arabidopsis thaliana*, the cereals and other crops are already contributing greatly to these efforts (Bennett, 2001). Much effort is currently being directed to developing molecular markers for the maximum rooting depth (Champoux *et al.*, 1995), the capacity of roots to penetrate hard pans (Ray *et al.*, 1996) and the capacity of the plant to osmotically adjust to water deficit (Lilley and Ludlow, 1996).

Opportunities and Challenges in the Adoption of Water-saving Practices

Growing rice in continuously flooded fields has been taken for granted for centuries, but the 'looming water crisis' may change the way rice is produced in the future. Water-saving irrigation technologies that were investigated in the early 1970s, such as SSC and AWD, are receiving renewed attention by researchers (Bouman and Tuong, 2001). The basic ingredients of implementing these technologies seem to be in place. But so far, except for China (Li, 2001), the adoption of these technologies has been slow. The challenge is to identify the environmental and socio-economic conditions that encourage farmers to adopt them. In this respect, our research is far from complete. We can, however, identify important factors that affect the farmers' acceptance of water-saving technologies.

Unlike fertilizers and pesticides, water is generally not actively traded on markets in Asia, and government-administered fees for irrigation water are often low or zero. This discourages farmers from treating water as a scarce resource. Farmers have no incentive to adopt water-saving technologies because water conservation does not reduce the farming expenditures nor does it increase income. It can be expected that, when water becomes a real economic good, farmers are more inclined to adopt water-saving technologies. There is evidence that farmers in Asia who are confronted with high costs of water already adopt such technologies. In certain areas in China, where farmers are charged by the volume of water they use, various forms of AWD and reduced floodwater depths have been widely adopted (Li, 2001). Farmers in north-central India (A.K. Singh, Los Baños, Philippines, April 2000, personal communication) who operate pumps to irrigate their fields consciously apply some form of AWD to save pumping costs. Experiences in Australia also show that water trading, by which farmers can sell their water rights to others, encourages farmers to adopt water-conservation measures.

Water-saving technologies that improve productivity and income will be readily accepted by farmers. Dry seeding is widely practised in drought-prone rain-fed systems because of its ability to increase rice yield and its stability and cropping intensity (My *et al.*, 1995; Saleh and Bhuiyan, 1995). In irrigated systems, however, water-saving technologies are mostly associated with some reduction in yield. Technologies that save water for rice and increase productivity of a post-rice crop will be more acceptable to farmers. The prospect of raised beds to increase the total system productivity of the rice–wheat system opens up opportunities to save water. Similarly, farmers may accept dry-seeding technologies in irrigated systems to reduce the labour cost of transplanting and wet land preparation.

All water-saving technologies, from SSC to AWD to dry seeding and aerobic rice, reduce water depth and expose rice-fields to periods without standing water. Poor levelling of rice-fields is common in Asia, leading to heterogeneity in the depth of standing water. This will result in a more competitive and diverse weed flora than in rice under conventional water management. On-farm research has shown that precise land levelling can improve the establishment of direct-seeded rice and increase water productivity (Hill *et al.*, 2001). Improving farmers' knowledge on improved (integrated) weed management will enhance their acceptance of water-saving technologies.

Suitable policies, institutional organization and legislation are needed to promote the adoption of water-saving technologies. The establishment of water-user groups and the implementation of volumetric water charging may be the most important elements behind the successful adoption of AWD in China. New laws prohibiting flooded rice cultivation in parts of the North China Plain and around Beijing are expected to increase farmers' interest in aerobic rice cultivation.

Environmental Impact and Challenges for Sustainable Management of Water-limited Rice Production Systems

Soil submergence is a unique feature of irrigated lowland rice ecosystems. Lowlands producing two or three rice crops per year on submerged soils are highly sustainable, as indicated by sustained nutrient supply capacity, sustained soil carbon levels and sustained trends in rice yields (Buresh *et al.*, 2001). However, the continuous submergence of soil promotes the production of methane, an important greenhouse gas, by the anaerobic decomposition of organic matter. Temporary soil aeration, such as under AWD, can reduce methane emission. Prolonged aeration of soil, such as in aerobic rice, can even reduce methane emission further. Soil aeration, on the other hand, can increase the emission of nitrous oxide, another greenhouse gas. Emissions of methane and nitrous oxide are strongly related to the soil redox potential, a measure of soil oxidation status. Hou *et al.* (2000) suggested that both methane and nitrous oxide emissions could be minimized by maintaining the soil redox potential within a range of -100 to +200 mV. An important research area is to assess whether water-saving technologies can achieve such an intermediate soil redox potential.

Increased soil aeration under AWD and in aerobic rice will also affect the capacity of soil organic matter and the capacity of the soil nutrient supply. The more competitive weed flora associated with water-saving technologies may require a greater reliance on herbicides (Naylor, 1996), which challenges environmental sustainability. Critical issues for water-saving technologies may include how much water and how frequent soil submergence is required for sustaining the productivity and services of rice ecosystems.

The impact of on-farm water saving on the role of water in sustaining environmental health warrants further investigation. In many basins, the drainage and percolation outflows from rice-fields return to the lower reaches of the rivers. They play an important environmental role in sustaining the fresh–saline water balance in estuaries. Reducing the outflows may result in increased salinity intrusion. The reported increased salinity in the Chao Phraya delta, Thailand, is an example. The drying up of the lower reaches of rivers and declining water tables (see examples in section under Water Resources in Rice-growing Areas) indicate that the basin is closing in such areas (Seckler, 1996) and that all the utilizable outflows from upstream have been reused. Water-saving practices that aim at reducing the drainage and percolation outflows from paddies are important options for farmers to maintain rice cultivation in the face of water scarcity, but they may not increase the water availability of the whole basin.

References

Abdullah, N. (1998) Some approaches towards increasing water use efficiency in the Muda irrigation scheme. In: *Proceedings of the Workshop on Increasing Water Productivity and Efficiency in Rice-based Systems, July 1998*. IRRI, Los Baños. Philippines.

Barker, R., Dawe, D., Tuong, T.P., Bhuiyan, S.I. and Guerra, L.C. (1999) The outlook for water resources in the year 2020: challenges for research on water management in rice production. In: *Assessment and Orientation Towards the 21st Century, Proceedings of 19th Session of the International Rice Commission, Cairo, Egypt, 7–9 September 1998*. FAO, Rome, pp. 96–109.

Bennett, J. (2001) Status of breeding for tolerance of water deficit and prospects for using molecular techniques. Paper presented at the International Workshop on Water Productivity, 12–13 November 2001, IWMI, Colombo, Sri Lanka.

Bhatti, M.A. and Kijne, J.W. (1992) Irrigation management potential of paddy/rice production in Punjab of Pakistan. In: Murty, V.V.N. and Koga, K. (eds) *Soil and Water Engineering for Paddy Field Management, Proceedings of the International Workshop on Soil and Water Engineering for Paddy Field Management, 28–30 January 1992*. Asian Institute of Technology, Bangkok, Thailand, pp. 355–366.

Bhuiyan, S.I., Sattar, M.A. and Khan, M.A.K. (1995) Improving water use efficiency in rice irrigation through wet seeding. *Irrigation Science* 16(1), 1–8.

Borell, A., Garside, A. and Shu Fukai (1997) Improving efficiency of water for irrigated rice in a semi-arid tropical environment. *Field Crops Research* 52, 231–248.

Bouman, B.A.M. (2001) *Water-efficient Management Strategies in Rice Production*. Notes 16.2, International Rice Research Institute (IRRI), IRRI, Los Baños, Philippines, pp. 17–22.

Bouman, B.A.M. and Tuong, T.P. (2001) Field water management to save water and increase its productivity in irrigated rice. *Agricultural Water Management* 49(1), 11–30.

Bouman, B.A.M., Wopereis, M.C.S., Kropff, M.J., Berge, H.F.M. and Tuong, T.P. (1994) Understanding the water use efficiency of flooded rice fields. II. Percolation and seepage losses. *Agricultural Water Management* 26, 291–304.

Bouman, B.A.M., Wang Hua Qi, Yang Xiao Guang, Zhao Jun Fang and Wang Chang Gui (2002) Aerobic rice (Han Dao): a new way of growing rice in water-short areas. In: *Proceedings of the 12th International Soil Conservation Organization Conference, 26–31 May 2002, Beijing, China.* Tsinghua University Press, Beijing, China, pp. 175–181.

Buresh, R.J., Dawe, D., Tuong, T.P., Ladha, J.K., Bouman, B.A.M., Lantin, R., Peng, S., Mortimer, M. and Hill, J.E. (2001) Sustainable soil and water management of irrigated rice ecosystems. Paper presented at the Integrated Management for Sustainable Agriculture, Forestry and Fisheries Workshop, 28–31 August 2001, Centro Internacional de Agricultura Tropical, Cali, Colombia.

Cabangon, R.J. and Tuong, T.P. (2000) Management of cracked soils for water saving during land preparation for rice cultivation. *Soil and Tillage Research* 56, 105–116.

Cabangon, R., Tuong, T.P., Tiak, E.B. and Abdullah, N.B. (2002) Increasing water productivity in rice cultivation: impact of large-scale adoption of direct seeding in the Muda irrigation system. In: *Direct Seeding in Asian Rice Systems: Strategic Research Issues and Opportunities. Proceedings of an International Workshop on Direct Seeding in Asia, Bangkok, Thailand, 25–28 January 2000*. IRRI, Makati City, Philippines, pp. 299–313.

Castañeda, A.R. and Bhuiyan, S.I. (1993) Sediment pollution in a gravity irrigation system and its effects on rice production. *Agriculture, Ecosystems and Environment* 45, 195–202.

Champoux, M.C., Wang, G., Sarkarung, S., Mackill, D.J., O'Tool, J.C., Huang N. and McCouch, S.R. (1995) Locating genes associated with root morphology and drought avoidance in rice via linkage to molecular markers. *Theoretical and Applied Genetics* 90, 969–981.

De Datta, S.K. (1981) *Principles and Practices of Rice Production*. IRRI, Los Baños, Philippines, 618 pp.

De Datta, S.K., Krupp, H.K., Alvarez, E.I. and Modgal, S.C. (1973) Water management in flooded rice. In: *Water Management in Philippine Irrigation Systems: Research and Operation*s. IRRI, Los Baños, Philippines, pp. 1–18.

Deju, Z. and Lu Jingwen (1993) The water-use efficiency of winter wheat and maize on a salt-affected soil in the Huang Huai river plain of China. *Agricultural Water Management* 23, 67–82.

Dong Bin, Loeve, R., Li, Y., Chen Chongde, Deng Li and Molden, D. (2001) Water productivity in Zhanghe irrigation system: issues of scale. In: Barker, R., Loeve, R., Li, Y. and Tuong, T.P. (eds) *Proceedings of the International Workshop on Water Saving Irrigation for Paddy Rice, 23–25 March 2001, Wuhan*. SWIM Publication, International Water Management Institute, Colombo, Sri Lanka, pp. 97–115.

Garrity, D.P., Oldeman, L.R. and Morris, R.A. (1986) Rainfed lowland rice ecosystems: characterization and distribution. In: *Progress in Rainfed Lowland Rice*. IRRI, Manila, Philippines, pp. 3–23.

Garrity, D.P., Vejpas, C. and Herrera, W. (1992) Percolation barriers increase and stabilize rain-fed lowland rice yields on well drained soils. In: Murty, V.V.N. and Koga, K. (eds) *Proceedings of the International Workshop on Soil and Water Engineering for Paddy Field Management, 28–30 January 1992*. Asian Institute of Technology, Rangsit, Thailand, pp. 413–421.

Hill, J.E., Mortimer, A.M., Namuco, O.S. and Janiya, J.D. (2001) Water and weed management in direct-seeded rice: are we headed in the right direction? In: Peng, S. and Hardy, B. (eds) *Rice Research for Food Security and Poverty Alleviation. Proceedings of the International Rice Research Conference, 31 March–3 April, 2000, Los Baños, Philippines*. IRRI, Los Baños, Philippines, pp. 491–510.

Hou, A.X., Chen, G.X., Wang, Z.P., Van Cleemput, O. and Patrick, W.H., Jr (2000) Methane and nitrous oxide emissions from rice field in relation to soil redox and microbiological processes. *Soil Science Society of America Journal* 64, 2180–2186.

Huke, R.E. and Huke, E.H. (1977) Rice area by type of culture: South, Southeast, and East Asia. A revised and updated database. IRRI, PO Box 933, Manila, Philippines.

IRRI (1998) *Sustaining Food Security Beyond the Year 2000: a Global Partnership for Rice Research, IRRI Rolling Medium-term Plan 1999–2001*. IRRI, Los Baños, Philippines.

IWMI (International Water Management Institute) (2000) *World Water Supply and Demand*. IWMI, Colombo, Sri Lanka.

Jha, K.P., Chandra, D. and Challaiah (1981) Irrigation requirement of high-yielding rice varieties grown on soils having shallow water-table. *Indian Journal of Agricultural Science* 51, 732–737.

Kam, S.P., Fajardo, S.D., Rala, A.B., Hossain, M., Tuong, T.P., Bouman, B.A.M. and Banik, P. (2000) *Multi-scale Drought Risk Analysis of Rainfed Rice Environment*. 30th Annual Scientific Conference of the Crop Science Societies of the Philippines, Batac, Ilocos Norte, Philippines.

Khepar, S.D., Sondi, S.K., Kumar, S. and Singh, K. (1997) *Modelling Effects of Cultural Practices on Water Use in Paddy Fields – a Case Study*. Research Bulletin, Publication No. NP/SWE-1, Punjab Agricultural University, Ludhiana, India.

Kitamura, Y. (1990) *Management of an Irrigation System for Double Cropping Culture in the Tropical Monsoon Area*. Technical Bulletin 27, Tropical Agriculture Research Centre, Ministry of Agriculture, Forestry and Fisheries, Tsukuba, Ibaraki, Japan.

Klemm, W. (1999) Water saving in rice cultivation. In: *Assessment and Orientation Towards the 21st Century. Proceedings of 19th Session of the International Rice Commission, Cairo, Egypt, 7–9 September 1998*. FAO, Rome, pp. 110–117.

Li., Y.H. (2001) Research and practice of water saving irrigation for rice in China. In: P*roceedings of the International Workshop on Water Saving Irrigation for Paddy Rice, 23–25 March 2001, Wuhan, China.* Wuhan University, Wuhan, China, pp. 135–144.

Lilley, J.M. and Ludlow, M.M. (1996) Expression of osmotic adjustment and dehydration tolerance in diverse rice lines. *Field Crops Research* 48, 185–197.

McCauley, G.N. (1990) Sprinkler vs. flooded irrigation in traditional rice production regions of southeast Texas. *Agronomy Journal* 82, 677–683.

Mishra, H.S., Rathore, T.R. and Pant, R.C. (1990) Root growth, water potential, and yield of irrigated rice. *Irrigation Science* 17, 69–75.

Moody, K. (1993) The role of water for weed control in direct-seeded rice. Paper presented at the Workshop on Water and Direct Seeding for Rice, 14–16 June 1993, Muda Agricultural Development Authority, Ampang Jajar, Alor Setar, Malaysia.

Moridis, G.J. and Alagcan, M. (1992) High-frequency basin irrigation design for upland crops in rice lands. *Irrigation and Drainage Engineering* 118, 564–583.

My, T.V., Tuong, T.P., Xuan, V.T. and Nghiep, N.T. (1995) Dry seeding rice for increased cropping intensity in Long An Province, Vietnam. In: Denning, G.L. and Vo-Tong Xuan (eds) *Vietnam and IRRI: a Partnership in Rice Research.* IRRI, Manila, Philippines, and Ministry of Agriculture and Food Industry, Hanoi, Vietnam, pp. 111–122.

Naylor, R. (ed.) (1996) *Herbicides in Asian Rice: Transitions in Weed Management*. Institute for International Studies, Stanford University, Stanford, and IRRI, Palo Alto, California, and Manila, Philippines, 270 pp.

Peng, S., Laza, R.C., Khush, G.S., Sanico, A.L., Visperas, R.M. and Garcia, F.V. (1998) Transpiration efficiencies of indica and improved tropical japonica rice grown under irrigated conditions. *Euphytica* 103, 103–108.

Pingali, P.L., Hossain, M. and Gerpacio, R.V. (1997) *Asian Rice Bowls: the Returning Crisis?* CAB International, Wallingford, UK, in association with IRRI, Los Baños, Philippines, 341 pp.

Pinter, P.J., Zipoli, G., Reginato, R.J., Jackson, R.D., Idso, S.B. and Hohman, J.P. (1990) Canopy temperature as an indicator of differential water use and yield performance among wheat cultivars. *Agricultural Water Management* 18, 35–48.

Postel, S. (1997) *Last Oasis. Facing Water Scarcity.* Norton, New York, 239 pp.

Ray, J.D., Yu, L., McCuch, S.R., Champoux, M., Wang, G. and Nguyen, H.T. (1996) Mapping quantitative trait loci associated with root penetration ability in rice (*Oryza sativa* L.). *Theoretical and Applied Genetics* 92, 627–636

Saleh, A.F.M. and Bhuiyan, S.I. (1995) Crop and rainwater management strategies for increasing productivity of rain-fed rice systems. *Agricultural Systems* 49, 259–276.

Sandhu, B.S., Khera, K.L., Prihar, S.S. and Singh, B. (1980) Irrigation need and yield of rice on a sandy-loam soil as effected by continuous and intermittent submergence. *Indian Journal of Agricultural Science* 50(6), 492–496.

Seckler, D. (1996) *The New Era of Water Resources Management*. Research Report 1, International Irrigation Management Institute, Colombo, Sri Lanka.

Sha, T., Molden, D., Sakthivadivel, R. and Seckler, D. (2000) *The Global Groundwater Situation: Overview of Opportunities and Challenges*. IWMI, Colombo, Sri Lanka.

Sharma, D.K., Kumar, A. and Singh, K.N. (1990) Effect of irrigation scheduling on growth, yield and evapotranspiration of wheat in sodic soils. *Agricultural Water Management* 18, 267–276.

Sharma, P.K., Ingram, K.T. and Harnpichitvitaya, D. (1995) Subsoil compaction to improve water use efficiency and yields of rain-fed lowland rice in coarse-textured soils. *Soil Tillage Research* 36, 33–44.

Shu Geng, Zhou, Y., Zhang, M. and Smallwood, K.S. (2001) A sustainable agro-ecological solution to water shortage in the North China Plain (Huabei Plain). *Journal of Environmental Planning and Management* 44, 345–355.

Stegman, E.C. (1982) Corn grain yield as influenced by timing of evapotranspiration deficits. *Irrigation Science* 3, 75–87.

Stockle, C.O., James, L.G., Bassett, D.L. and Saxton, K.E. (1990) Effect of evapotranspiration underprediction on irrigation scheduling and yield of corn: a simulation study. *Agricultural Water Management* 19, 167–179.

Tabbal, D.F., Lampayan, R.M. and Bhuiyan, S.I. (1992) Water-efficient irrigation technique for rice. In: Murty, V.V.N. and Koga, K. (eds) *Soil and Water Engineering for Paddy Field Management. Proceedings of the International Workshop on Soil and Water Engineering for Paddy Field Management, 28–30 January 1992.* Asian Institute of Technology, Bangkok, Thailand, pp. 146–159.

Tabbal, D.F., Bhuiyan, S.I. and Sibayan, E.B. (2002a) Dry-seeding technique for saving water in irrigated rice production systems. In: *Direct Seeding in Asian Rice Systems: Strategic Research Issues and Opportunities. Proceedings of an International Workshop, on Direct Seeding in Asia, Bangkok, Thailand, 25–28 January 2000*. IRRI, Makati City, Philippines, pp. 281–297.

Tabbal, D.F., Bouman, B.A.M., Bhuiyan, S.I., Sibayan, E.B. and Sattar, M.A. (2002b) On-farm strategies for reducing water input in irrigated rice: case studies in the Philippines. *Agricultural Water Management* 56(2), 93–112.

Thompson, J. (1999) Methods for increasing rice water use efficiency. In: *Rice Water Use Efficiency Workshop Proceedings.* CRC for Sustainable Rice Production, Lecton, pp. 45–46.

Tuong, T.P. (1999) Productive water use in rice production: opportunities and limitations. *Journal of Crop Production* 2(2), 241–264.

Tuong, T.P., Cabangon, R. and Wopereis, M.C.S. (1996) Quantifying flow processes during land soaking of cracked rice soils. *Society of Soil Science America Journal* 60(3), 872–879.

Tuong, T.P., Pablico, P.P., Yamauchi, M., Confesor, R. and Moody, K. (2000) Increasing water productivity and weed suppression of wet seeded rice: effect of water management and rice genotypes. *Journal of Experimental Agriculture* 36, 1–19.

Turner, N.C. (1997) Further progress in crop water relations. *Advanced Agronomy* 58, 293–338.

Wang Huaqi, Bouman, B.A.M., Dule Zhao, Wang Changgui and Moya P.F. (2003) Aerobic rice in northern China – opportunities and challenges. In: Bouman, B.A.M., Hengsdijk, H., Hardy, B., Bidraban, P.S., Tuong, T.P., Lafitte, R. and Ladha, J.K. (eds) *Water-wise Rice Production.* IRRI, Los Baños, Philippines, pp. 143–154.

Wei Zhang and Si-tu Song (1989) Irrigation model of water saving-high yield at lowland paddy field. In: *International Commission on Irrigation and Drainage, Seventh Afro-Asian Regional Conference, 15–25 October 1989*, Vol. I-C. ICID (International Commission for Irrigation and Drainage), Dehli, India, pp. 480–496.

Westcott, M.P. and Vines, K.W. (1986) A comparison of sprinkler and flooded irrigation for rice. *Agronomy* 78, 637–640.

Wickham, T.H. and Singh, V.P. (1978) Water movement through wet soils. In: *Soils and Rice.* IRRI, Los Baños, Philippines, pp. 337–358.