

More Rice, Less Water—Integrated Approaches for Increasing Water Productivity in Irrigated Rice-Based Systems in Asia

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Abstract

The water crisis is threatening the sustainability of the irrigated rice system and food security in Asia. Our challenge is to develop novel technologies and production systems that allow rice production to be maintained or increased in the face of declining water availability. This paper introduces principles that govern technologies and systems for reducing water inputs and increasing water productivity, and assesses the opportunities of such technologies and systems at spatial scale levels from plant to field, to irrigation system, and to agro-ecological zones. We concluded that, while increasing the productivity of irrigated rice with transpired water may require breakthroughs in breeding, many technologies can reduce water inputs at the field level and increase field-level water productivity with respect to irrigation and total water inputs. Most of them, however, come at the cost of decreased yield. More rice with less water can only be achieved when water management is integrated with (i) germplasm selection and other crop and resource management practices to increase yield and (ii) system-level management such that the water saved at the field level is used more effectively to irrigate previously un-irrigated or low-productivity lands. The amount of water that can be saved at the system level could be far less than assumed from computations of field-level water savings because there is already a high degree of recycling and conjunctive use of water in many rice areas. The impact of reducing water inputs for rice production on weeds, nutrients, sustainability, and environmental services of rice ecosystems warrants further investigation.

Media summary

Producing more rice with less water is possible but systems approaches are needed to understand the cross-scale impact, and to minimize the side effects, of reducing water inputs to rice fields.

Key Words

Water saving, water management, irrigation, sustainability, environment, food security

Introduction

The present and future food security of Asia depends largely on the irrigated rice production system: more than 75% of the rice supply comes from 79 million ha of irrigated land. To produce 1 kg of grain, farmers have to put 2 to 3 times more water in rice fields than in those growing other cereals, and, in Asia, the amount of water used to irrigate rice fields accounts for about 50% of all diverted freshwater (Barker et al. 1998). Recent years have seen a growing scarcity of water worldwide; the pressure to reduce water use in irrigated agriculture is mounting. Actively reducing the amount of water used in rice can have a positive societal and economic impact if the water saved is diverted to areas where competition from industry, cities, and the environment is high. There is also much evidence that water scarcity already prevails in rice-growing areas (Tuong and Bouman 2002), where rice farmers need technologies to cope with water shortage and ways must be sought to grow rice with less water. However, rice is very sensitive to water stress and attempts to reduce water inputs may result in yield reduction. The challenge is to develop novel technologies and production systems that will allow rice production to be maintained or increased in the face of declining water availability. This paper introduces principles that govern technologies and systems for reducing water inputs and increasing water productivity, and assesses the opportunities of such technologies and systems at spatial scale levels from plant to field, to irrigation system, and to agro-ecological zones. The paper also discusses the negative impacts that water-saving technologies may have on the environment and on the sustainability of rice production.

Framework for assessing water productivity and water saving

Relevance of water productivity

Water productivity (WP) is a concept of *partial productivity* and denotes the amount or value of product over volume or value of water used. Discrepancies are large in reported values of WP of rice (Tuong

1999). These are partially due to large variations in rice yields, with commonly reported values ranging from 3 to 8 tons per hectare. But the discrepancies are also due to different understandings of the denominator (water used) in the computation of WP. For example, the amount of water “used” to produce 1 kg of rice is in the range of 500–2000 kg if only evapotranspiration is taken into account (Tuong, 1999). This is one-half to one-third the WP-values reported by others (e.g., in Bouman and Tuong, 2001), who may compute WP with respect to the total water inputs to the rice field. To avoid confusion created by different interpretations and computations of WP, it is important to clearly specify what kind of WP we are referring to and how it is derived. Which parameter should go in the denominator depends on the objective of the study under consideration, which may vary among interested groups. While breeders are interested in the productivity of the amount of transpired water (WP_T), farmers and irrigation engineers/managers are interested in optimising the productivity of irrigation water (WP_I). To regional water resources planners, who are interested in the amount of food that can be produced by total water resources (rainfall and diverted water) in the region, water productivity with respect to the total water input (WP_{TWI}) may be more relevant.

Comparing WP among seasons and locations can be misleading. It is more relevant to study what the potential and actual WP values are in a particular environment, and to identify measures to close the gaps between them, rather than to compare WP values across environments (and sometimes years). For example, in rainy seasons, a small amount of supplementary irrigation can lead to very high WP_I levels (e.g., > 10 kg rice m^{-3} irrigation water in Tuan Lin, China, Cabangon et al. 2003) because rainfall supplies most of the water needed for crop growth. This does not mean that irrigation water is better used in the rainy season than in the dry season. The impact of the supplementary irrigation can be better assessed by the “incremental irrigation water productivity”, defined as the increase in the amount or value of the product (compared with no irrigation) over the volume of supplementary irrigation water. Unfortunately, data on this kind of water productivity are scarce.

Saving water or reducing water inputs?

Water-saving measures often refer to technologies that lead to a reduction in the water supply to a particular domain of interest. The term is most appropriate when water is a scarce resource and when the amount of water saved can be either stored and used later in the same domain or diverted to another place for use there. Perceptions of saving water vary with stakeholders’ point of view. In a water-short region or basin, policymakers and resource-use planners may like to reduce the supply of water to rice fields (where water is abundant or adequate) so that more water can be diverted to other areas or sectors of society. Rice farmers who are enjoying water adequacy, however, may not feel a need to reduce water inputs and “save” water unless water-saving technologies benefit them (e.g., reduced cost of water supply, increased yield, etc.).

Reducing water inputs is not always synonymous with saving water. In areas where water is already scarce, farmers must be equipped with technologies to grow rice with less water, not to save water (since there is no water to save), but simply because there is not enough water to grow rice in the conventional way.

Principles for saving water and increasing water productivity

Because of the scale-dependency of water productivity and water savings (Molden et al. 2003), to assess WP-enhancing and water-saving measures it is important (i) to identify the boundary of the domain of interest and (ii) to study the crop production characteristics and water-flow processes within the domain of interest and understand how these processes change as we move across scales. In its simplest form, crop production (Pr) is related to crop stomatal transpiration (T):

$$Pr = WP_T * T \quad [1]$$

The interdependence of the different water components in a domain is governed by the water balance equation:

$$Q_{in} = Q_{out} + \Delta S \quad [2]$$

Q_{in} represents the collective water-supply components, which can constitute irrigation water (I) and other (non-irrigation) water inputs ($AInf$) such as rainfall, capillary flow from a shallow watertable, and net lateral flow from adjacent areas. Q_{out} represents the collective outflow components, including crop stomatal transpiration (T), other non-beneficial depletions to the atmosphere (E , such as evaporation from wet soil, transpiration from weeds, etc.), and outflows ($Outf$) to the surrounding areas (e.g., seepage and percolation). ΔS represents the change in storage of water in the domain of investigation. Equation [2] can be written as

$$\begin{aligned} I + AInf &= T + E + Outf + \Delta S \\ T &= I + AInf - E - Outf - \Delta S \end{aligned} \quad [3]$$

From [1] and [3]

$$Pr = WP_T * (I - E - Outf + AInf - \Delta S) \quad [4]$$

In the context of irrigated rice systems, the objectives of WP-enhancing and water-saving measures are (i) to maximise crop production, or its value, and (ii) to minimise the use or cost of the expensive/scarce irrigation water without affecting the water available to crop transpiration. From equations [1] and [4], these objectives can be obtained by 5 principles:

1. Enhancing WP_T
2. Reducing non-beneficial depletions, E
3. Reducing outflows, $Outf$
4. Effectively using other (non-irrigation) inflows to the domain of interest, $AInf$
5. Effectively using water from the storage (and therefore reducing its storage size, $-\Delta S$) in the domain of interest as a source of water supply.

The following sections will examine strategies and technologies that reduce water inputs and enhance water productivity at different scales.

Strategies and technologies for increasing water productivity at the plant level

At the plant level, the system boundaries are the outside of the plant (above ground and below ground). The only water inflow into the system is water taken up by the roots and the only outflow is water transpired. Only principles 1 and 2 are applicable at the plant level.

Rice breeding over the last decades has contributed to increasing WP_T by increasing yields together with reducing crop growth duration (and hence reducing seasonal transpiration, Tuong 1999). Grain yield is the product of (i) the amount of biomass produced by photosynthesis and (ii) the amount of biomass partitioned to the grains, usually expressed as harvest index (HI). Most of the increases in rice yield in the last decades were achieved by improvements in HI. Some have argued that HI may now be approaching its theoretical limit in many major crops (Richards et al. 1993). The photosynthesis process generally governs biomass production per unit water transpired, or water use efficiency (WUE). Although there is little difference in photosynthesis rate among different commonly grown rice varieties, Peng et al. (1998) reported that WUE was some 25–30% higher for tropical japonica than for indica rice types. This implies that significant variation may exist in rice germplasm for photosynthesis-transpiration ratio and that this could be investigated further to enhance WP_T of rice. Some researchers, however, argue that, to improve WP_T of rice, one has to radically change the photosynthetic process of the plant, such as incorporating the C₄ photosynthetic pathway (J. Sheehy, personal communication). The role of transpiration in keeping the canopy cool is a potential source of difficulty for breeding to increase WP_T . This and constraints to reducing transpiration through the cuticle (non-beneficial depletions at the plant level) without affecting yield are discussed in Bennett (2003).

Strategies and technologies for reducing water inputs and increasing WP at the field level

At the field level, the domain boundaries are the top of the canopy, the bottom of the root zone, and the horizontal field boundaries. The reported amount of total water input into a rice field ranges from 900 to more than 3000 mm, though the transpiration demand of the crop in the tropics is in the range of 350 to 550 mm only (Tuong 1999, Bouman and Tuong 2001, Tuong and Bouman 2002). Water is also lost into

the atmosphere via evaporation during the land preparation period (100–180 mm), via evaporation from soil or water surfaces in between rice plants (150–200 mm), and via transpiration from weeds. The outflows consist mainly of the bypass flow during land preparation (350–1500 mm) and seepage and percolation (300–1500 mm) during the crop growth period. The field-level WP_{TWI} varies widely (Fig. 1) and there are many opportunities to enhance WP and reduce water inputs at the field level, following the 5 principles above.

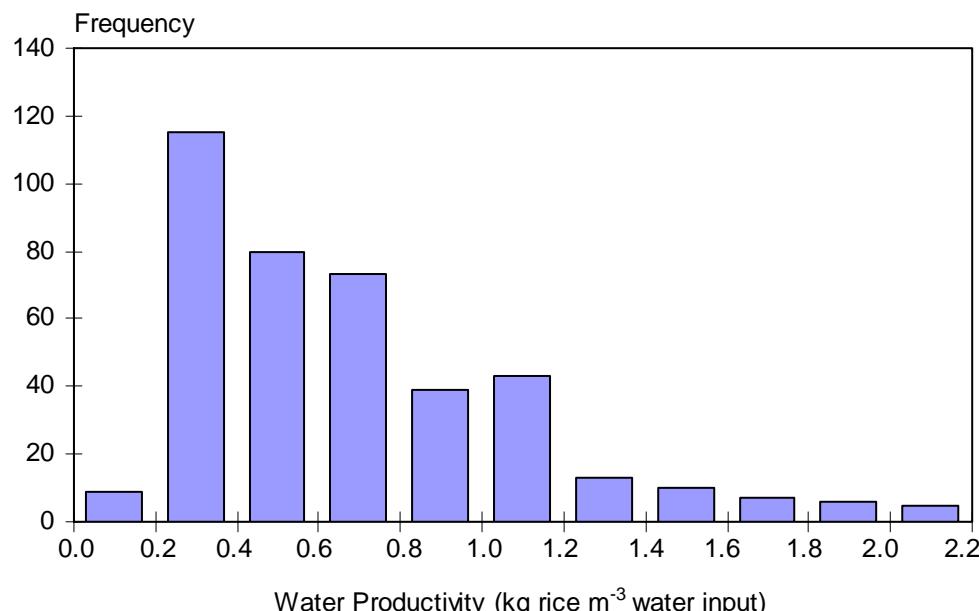


Figure 1. Frequency distribution of water productivity with respect to total water inputs from field experiments in India, the Philippines, China, and Malaysia. Most of the data on the left of the x-axis are from India, with local varieties on light soils and deep groundwater table, while those on the right are from China, with hybrid rice, clay soil, and shallow groundwater table. (Sources: Bouman and Tuong 2001, Cabangon et al. 2002, Cabangon et al. 2003)

1. Enhancing WP_T

Good crop husbandry that supplies an adequate and balanced amount of nutrients and reduces weeds, pests, and diseases will enhance canopy development and increase yield. For a given crop and soil fertility, the potential biomass accumulation largely depends on the amount of radiation that the canopy intercepts. Evaporation and transpiration, on the other hand, are driven also by other climatic factors, such as temperature, wind speed, and the vapour pressure deficit of the atmosphere. These climatic parameters vary widely from region to region and from season to season. It is therefore possible to change the biomass production per unit transpiration by adjusting the growing season (Stanhill 1986). Untimely planting may lead to high yield loss due to high spikelet sterility caused by chilling or high temperatures (Wopereis, 1998). The variation in WP_T caused by variation in planting date is larger in a temperate climate than in a tropical equatorial climate (Stanhill 1986).

2. Reducing non-beneficial depletions

One obvious measure to reduce evaporation is to shorten the land preparation period (Tuong 1999). Early canopy closure will help to reduce evaporation after crop establishment. This can be achieved by proper plant density and by growing rice varieties with good seedling vigour. These measures also help the rice plants compete better with weeds, thus reducing non-beneficial transpiration from weeds and increasing yield (Tuong et al. 2000). Other weed control practices, including good land levelling, timely flooding, manual weeding, and the use of herbicides, also contribute to reducing non-beneficial transpiration from weeds.

Water surfaces have a higher evaporation rate than soil surfaces. Technologies such as alternate wetting and drying (AWD) irrigation, bed planting, and aerobic rice systems (see below) that reduce the duration that the field is flooded will also decrease the amount of evaporation. Unfortunately, there are few quantitative data on the impact of these technologies on evaporation losses (Bouman et al. 2004). Recently, soil mulching has been shown to reduce water inputs and increase water productivity in rice,

especially in combination with non-saturated, aerobic soil conditions. Plastic sheets are especially effective in eliminating evaporation from bare soil and in suppressing weeds (Dittert et al. 2002).

Most of the measures to reduce non-beneficial depletions come at a labour or financial cost.

3. Reducing outflows

A high amount of outflow occurs in flooded rice production because of the presence of the water layer, which creates a hydrostatic water pressure that forces water movement through the soil. This outflow can be reduced by decreasing the rate of flow or by reducing the duration that fields are flooded. Technologies that reduce the rate of outflow can broadly be classified into (i) soil management practices to increase resistance to water flow and (ii) water management practices to reduce the hydrostatic pressure (Tuong et al. 1994).

a. Soil management to increase resistance to water flow

Puddling increases the hydraulic resistance of the plow sole that impedes vertical water movement during the crop growth period (Tuong et al. 1994). The efficacy of puddling in reducing percolation depends greatly on soil properties. Puddling is very efficient in clay soils that form cracks during the fallow period that penetrate the (semi-)impermeable subsoil layer (Tuong et al. 1994). Puddling may not be effective in coarse soils, which do not have enough fine clay particles to migrate downward and fill up the cracks and pores in the plow sole. Despite reducing percolation losses during the crop growth phase, puddling does not necessarily reduce the total water requirement for rice (Guerra et al. 1998, Tabbal et al. 2002). This is due to the high amount of by-pass flow through soil cracks during land soaking prior to puddling. Cabangon and Tuong (2000) showed the beneficial effects of additional shallow soil tillage before land soaking to close the cracks. Soil compaction using heavy machinery has been shown to decrease soil permeability in northeast Thailand in sandy soil with loamy subsoils with at least 5% clay (Harnpichitvitaya et al. 2000). However, most farmers cannot afford to do soil compaction.

b. Water management to reduce hydrostatic pressure and minimise outflows

Figure 2 illustrates technologies to reduce water inputs by minimising outflows. Instead of keeping the field continuously flooded with 5–10 cm of water, the floodwater depth can be decreased, the soil can be kept around saturation (SSC; saturated soil culture), or AWD regimes can be imposed. When water is really scarce, farmers may have to adapt aerobic rice systems, in which irrigation methods for upland crops such as sprinkler or furrow irrigation can be used.

In SSC, the soil is kept as close to saturation as possible by shallow irrigations to obtain about 1-cm floodwater depth a day or so after the disappearance of standing water. Tabbal et al (2002) reported that SSC reduced water inputs by 30–60% compared with the conventional practice in Central Luzon, Philippines. The yield reduction was only 4–9%, resulting in an increase in WP_{TWI} of 30–115%. Implementing SSC requires good water control at the field level. Moreover, frequent shallow irrigations are labour-intensive. Borrell et al (1997) experimented with raised beds in Australia to facilitate SSC practices. In this system, rice is grown on beds that are kept at saturation by water in furrows in between the beds. While most researchers agreed that bed planting reduced water inputs compared with conventional flooding, reports on its effects on rice yield and water productivity have been diverse (Borrell et al. 1997, Thompson 1999, Gupta et al. 2002). In a recent experiment at IRRI, Tuong (2003) reported that bed planting, in which water was applied to the furrows when soil water potentials at 15-cm depth at the centre of the bed reached threshold values of about –20 kPa, reduced water inputs by 42% compared with conventional flooded rice grown in flat fields. Though yield declined by 17%, the WP_{TWI} of bed planting was 33% higher than that in the conventional flooded system. However, bed planting had a WP_{TWI} similar to that of rice grown in conventional flat fields that were intermittently irrigated at the same threshold soil water potentials as the beds. This implies that farmers have the option, depending on their production environment, to use either flat fields or raised beds to reduce water inputs, increase water productivity, and accept some yield penalty. Raised beds and furrows may facilitate water distribution. In rice-wheat and other rice-upland systems, bed planting may also facilitate the establishment of upland crops after rice because beds and furrows improve drainage when rainfall is heavy (Humphreys et al. 2004).

In AWD, irrigation water is applied to obtain 2–5-cm floodwater depth after a certain number of days (ranging from 2 to 7) have passed after the disappearance of standing water. Rice yield, water inputs, and water productivity in AWD depend very much on environmental conditions, especially soil type, depth of groundwater, and the number of days passed after the disappearance of standing water. When the groundwater is within the rooting depth of the rice plant, the drying periods in AWD do not expose the rice plants to much water stress, and rice yields are comparable with, or only slightly lower than, rice yields under flooded conditions. When the groundwater table is beneath the rooting depth of the rice plants, AWD results in some yield decrease compared with continuously flooded systems. Cabangon et al. (2003) reported that yield declined significantly in AWD when the soil water potentials at 10-cm depth dropped below -20 kPa. These results are comparable with those of Hira et al. (2002), who reported that yield was not affected and that irrigation water savings of 550 mm were achieved when rice was irrigated when the soil water potential at 15–20-cm depth reached -8 to -16 kPa. These findings support the suggestion that irrigation scheduling is better done on the basis of soil water potential than on the number of days after the disappearance of standing water. In general, AWD reduces both water inputs and rice yield, but, in most cases, the reduction in water inputs is higher than that in yield so that water productivity increases (Bouman and Tuong 2001).

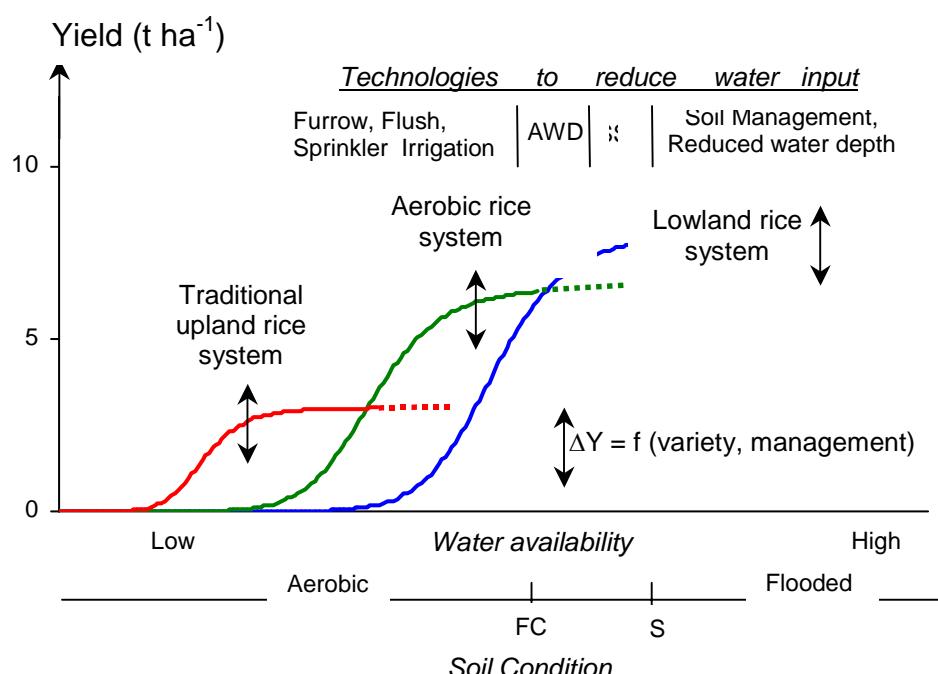


Figure 2. Schematic presentation of yield responses to water availability and soil condition in different rice production systems and their respective technologies to reduce water inputs. AWD = alternate wetting and drying, SSC = saturated soil culture, FC = field capacity, S = saturation point, ΔY = change in yield.

Aerobic rice system. A fundamental approach to reduce water inputs in rice is to grow the crop like an irrigated upland crop such as wheat or maize, that is, on non-puddled, aerobic soil without standing water. The potential water savings when rice can be grown as an irrigated upland crop are large, especially on soils with high seepage and percolation rates. Traditional upland rice varieties are grown this way, but they have been selected to give stable but low yields in adverse environments where water availability is very low (Fig. 2). On the other hand, high-yielding lowland rice grown under aerobic conditions shows great potential to save water, but at a severe yield penalty (see curve for “flooded rice system”, Fig. 2).

New varieties that are high yielding and responsive to inputs in aerobic conditions must be developed if the concept of growing rice like an irrigated upland crop is to be successful. Bouman (2003) recently coined the term “aerobic rice” to describe a system of growing high-yielding rice varieties in non-puddled, aerobic soil (Fig. 2). Evidence for its feasibility comes from Brazil and northern China (Bouman 2003). In North China, rice cultivars called Han Dao have been developed that yield up to $6\text{--}7 \text{ t ha}^{-1}$ under flush irrigation (Wang Huaqi et al. 2002). Recent experiments near Beijing showed that water savings of more than 50% compared with flooded lowland rice can be realized (Yang Xiaoguang et al. 2002). More

importantly, yields of 4–5.5 t ha⁻¹ were obtained using extremely little water (550–650 mm, versus 1340 mm under lowland conditions, resulting in soil water potentials below –100 kPa).

Some tropical rice varieties also have a relatively high yield under aerobic soil conditions. In a recent study in the Philippines, the improved upland variety Apo yielded up to 5.7 t ha⁻¹ and the lowland hybrid rice Magat up to 6 t ha⁻¹ in the dry season (Bouman et al. 2004). Though yields were on average 26% lower than under flooded conditions, water inputs were 44% lower and water productivities 35% higher. The high yields, however, were obtained in relatively wet aerobic soil conditions, with soil moisture potential at

10–15-cm depth not less than –10 to –12 kPa. Further investigation is needed on the yield performance of these varieties under dryer soil conditions. Special breeding is probably required to maintain high yield levels under soil moisture conditions below field capacity, especially to maintain spikelet fertility.

4. Effective use of other (non-irrigation) inflows such as rainfall

In transplanted and wet-seeded 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 the crop can be established using early monsoon rainfall. Because of its early establishment, dry-seeded rice can use rainfall more effectively than other establishment methods. Cabangon et al. (2002) reported that dry-seeded rice yielded slightly less, but had a significantly higher WP_I than wet-seeded and transplanted rice in the Muda Irrigation Scheme, Malaysia. However, all three establishment methods had a similar WP_{TWI} and total water inputs, indicating that dry-seeded rice does not reduce irrigation water when rainfall is low, for example, in the dry season.

5. Effective use of stored water in the domain of interest

In publicly-run irrigation systems, water delivery does not always match field water requirements. When this mismatch occurs during flowering, it can cause severe yield loss. In such cases, farmers may need to increase the depth of the ponded water layer as a means of safeguarding against a delay in water delivery. It should be noted, however, that this approach is at the expense of increased outflows (see above). The use of non-conventional water resources and water with marginal quality offers great promise for water-scarce areas. Potential sources include natural brackish water, agricultural drainage water, and treated sewage effluent as discussed in Kijne et al. (2003) and Tyagi (2003).

Trade-offs and challenges: cross-scale interactions, environment, and sustainability

Interactions among scales: are water savings real?

Since non-beneficial depletions are permanently lost to the atmosphere and cannot be “reused”, reducing them at the field level has positive effects on higher scales as well (system, basin levels). Similarly, the effect of enhancing WP_T in individual fields will transcend across scales. Crop performance in the individual field in an irrigation system, however, depends a great deal on the timely delivery of water to meet crop demand. Mistiming of irrigations results in low WP_{TWI} (Smith et al. 1985) and, if a water deficit occurs at crop anthesis, WP_T will also decrease. Similarly, shortening the duration of land preparation and the fallow period to reduce non-beneficial depletions may also depend on system-level infrastructure. For example, Abdullah (1998) reported that increasing canal and drainage intensities in the Muda Irrigation Scheme, from 10 m ha⁻¹ to 30 m ha⁻¹, enabled farmers to shorten their land preparation by 25 days, resulting in an annual water savings of 375 mm in two rice-cropping seasons. This author indicated, however, that tertiary infrastructure was costly; the economic rate of return in areas with tertiary facilities was only 6% compared with 12% in areas without tertiary channels.

The impact of technologies that reduce field-level outflows on a larger scale (e.g., system, basin level) depends on how current outflows from the field are used. Water-saving measures at the field level produce more rice and increase WP_I or WP_{TWI} at a larger scale only if the amount of water saved is used more productively elsewhere than before it was “saved”. Most of the outflows from the field go into drainage canals or recharge aquifers. In many cases, the outflows from the field are being reused already downstream through pumping from creeks, drains, or shallow groundwater. In a rice irrigation system in Niigata Prefecture, Japan, average drainage water reuse was about 14–15% of the original irrigation water inflow (Zulu et al. 1996). In the Upper Pampanga River Integrated Irrigation System (UPRIIS), Philippines, 15% of the water delivered to the system was recycled, servicing 18% of the farmers and 23% of the service area (100,000 ha) of the system (Hafeez 2003). The increased use of groundwater for

the last few decades has considerably enhanced the availability of irrigation water at the farm gate in semi-arid countries, for example, in large parts of India's and Pakistan's Punjab. The effective recycling of drainage water and conjunctive use of groundwater pose a question whether we should apply technologies such as SSC, AWD, and aerobic rice to reduce field-level outflows or investment should be made in recycling outflows. The choice obviously depends on the relative cost-effectiveness of the strategies. Land quality, labor cost and availability, and market will be important factors to determine where "more rice" is produced.

Nutrients

Changes from saturated to (partially) aerobic soil conditions affect the form, availability, and loss processes of nutrients such as phosphorus and nitrogen (Willett et al. 1982; Muirhead et al. 1989). Under flooded conditions, most N is available and taken up as ammonium. In raised beds and flat land under AWD irrigation regimes, nitrate can be formed during periods of dry soil. Tabbal et al. (1992) showed that the level of ammonium in the soil was lower, and that of nitrate higher, in AWD than in flooded rice fields. Upon subsequent flooding, nitrate could be leached or undergo denitrification losses and N losses may be higher in AWD than in conventional flooding. However, Belder et al. (2004) found similar N uptake and (fertilizer-N) recoveries under flooded and AWD conditions, in experiments where shallow groundwater tables kept the soil relatively wet during non-submerged periods. Further research is needed to determine the level of "dryness" in AWD, which does not reduce N-use efficiency. In light-textured, alkaline soils with a high pH, the availability of micronutrients may become a problem under conditions of non-saturated soil as occurs in AWD, raised beds, and aerobic rice. Sharma et al. (2002) and Singh et al. (2002) reported iron and zinc deficiencies in raised beds and in direct-seeded systems under an AWD irrigation regime.

Weeds

Standing water into which rice is transplanted suppresses weed growth because of the dual effects of the reduction in weed germination and establishment by water, and the inherent size advantage of the crop. Switching from transplanting to direct seeding in rice establishment removes that suppressive advantage and changes the composition of the weed flora. In Malaysia, the change from transplanting to direct seeding of rice onto saturated puddled soil resulted in the inclusion of 21 new weed species into the community and the exclusion of 15 others in six seasons (Mortimer and Hill 1999). Weed species shifts similarly occur with the adoption of dry seeding and zero tillage, with annual grass weeds in particular becoming more problematic. For example, in the rice-wheat system of India, trials of drill seeding with conventional tillage and shallow (10–30 mm) flooding up to 30 DAS indicate that *Ischaemum rugosum* and *Leptochloa chinensis* may become highly abundant together with *Eragrostis japonica* whilst decreasing the abundance of *Paspalum* spp. and *Cyperus rotundus*. Contrastingly, under zero tillage, *Commelina diffusa* and *Cyperus rotundus* become the dominant weed species.

In the absence of weed control, weed infestation may cause a complete yield loss in direct-seeded rice. Protection of yield from weed competition in all direct-seeded systems requires early-season weed control. Weeding at 30 DAS under all direct-seeding systems recovers a significant yield fraction and further gains can be accrued with more intensive weeding where dry-direct seeded rice may have yield similar to that of transplanted rice (Singh et al. 2003).

AWD and bed planting, respectively, introduce temporal and spatial variation in the water supply. A potential consequence of this is patchiness in weed communities and increased diversity of the weed flora as a result of differing water regimes for weed germination and establishment. This emphasizes the need for broad-spectrum herbicide use or serial application of herbicides, particularly late post-emergence graminicides. AWD in transplanted rice typically results in species pre-adapted for persistence under short-duration shallow flooding such as *Echinochloa colona*. The abundance of weeds and the composition of the weed flora in aerobic rice systems have not been investigated systematically, but it is expected that weed infestation will increase with more upland weed species.

Sustainability

Continuously submerged soils, despite changes in soil organic matter quality (Olk and Senesi, 2000), have remarkable long-term sustainability in nutrient-supplying capacity, maintenance of soil C (soil organic matter), and yield (Dawe et al. 2000). Studies are limited on yield sustainability in aerobic

systems, but initial reports suggest that yield declines when rice is continuously grown under aerobic conditions. George et al. (2003) reported a rapid yield decline under continuous upland rice cropping in the Philippines. Likely causes for any yield decline are the build-up of soil-borne pathogens such as nematodes. In recent experiments in central Luzon, Philippines, nematodes completely devastated a dry-season aerobic rice crop immediately following a wet season where up to 5 t ha⁻¹ of aerobic rice was harvested in the same field (Bouman, unpublished data). Bouman et al. (2004) reported that after six seasons of continuous aerobic rice cropping, there was a gradual yield decline in variety *Apo* (compared with flooded conditions) but such a trend was not obvious when all tested varieties were averaged together. The yield decline in aerobic rice systems needs further investigation.

Environmental impacts

The continuous submergence of soil under flooded rice promotes the production of methane, an important greenhouse gas. Temporary or complete soil aeration, such as in AWD or aerobic rice, respectively, can reduce methane emission. Soil aeration, on the other hand, can increase the emission of nitrous oxide, another greenhouse gas. Ditttert et al. (2002) reported decreased levels of methane emission and increased levels of NO and N₂O emissions in aerobic rice systems with different types of surface cover (mulch) compared with flooded rice systems. The trade-off between decreased methane and increased N₂O emissions depended on soil type, groundwater depth, fertilizer application rate, and soil water content. Hou et al. (2000) suggested that both methane and nitrous oxide emissions could be minimised 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.

The rural poor in tropical Asia frequently obtain water for drinking and household use from shallow aquifers under agricultural land. Bouman et al. (2001) reported very low nitrate concentration in shallow aquifers in areas with one or two rice crops per year. Nitrate concentrations near and above the limit of 10 mg N L⁻¹ of the World Health Organization were observed only in areas with high-valued upland crops (year-round or in rotation with rice) using extremely high amounts of N fertilizer. Soil submergence restricts the conversion of fertilizer N into nitrate, thereby limiting the amount of nitrate available for lateral and downward movement in flooded rice systems. As mentioned above (nutrient section), the presence of aerobic conditions in raised beds, AWD, and aerobic rice systems will favour the formation of nitrate with subsequent risks of leaching into the groundwater in the case of over-fertilization.

The cost-benefit ratio of pre-emergence and/or early post-emergence herbicide regimes strongly favours chemical as opposed to manual weeding (Moody 1996). Extensive reliance on herbicides has led to the widespread evolution of herbicide resistance, particularly in the Gramineae (Mortimer 2001), including *E. crus-galli* and *E. colona*. The need to implement weed management programs that vitiate the evolution of herbicide resistance will be important in water-scarce conditions and this emphasizes the need for integrated weed management. The intensive use of herbicides in agro-ecosystems that do not separate water supplies for human use and for agricultural use raises both health and wider environmental issues. Hill et al. (1997) described the deleterious environmental impacts (fish kills/ poor water quality) of the widespread use of molinate and thiobencarb for *Echinochloa* control in California rice production. Successful mitigation of the environmental effects of these herbicides was achieved by water holding and water reuse after herbicide application in relation to degradation rates. In Asia, however, the short-term fate of herbicides and their degradation products remains unresearched and a pressing concern both in rural areas and where urban communities draw on water supplies from agricultural land (Moody 1996).

The impact of reducing outflows from rice fields on the environment warrants further investigation. The multi-functionality of rice fields has been well recognized (Chieng 2003). In many basins, outflows from rice fields recharge the groundwater and supply water to natural wetlands. They can also play an important environmental role in sustaining the fresh-saline water balance in estuaries. Reducing outflows may result in drying out wetlands, or in increased salinity intrusion, which disrupts coastal environments.

Conclusion

Progress in rice science in recent decades has greatly enhanced WP_T. While a further increase in WP_T in irrigated rice is likely to require breakthroughs in breeding, with the help of biotechnology, many technologies can reduce water inputs at the field level (or help farmers to better cope with water scarcity) and increase field-level WP_I and WP_{TWI}. Most of them, however, come at the cost of decreased yield (or

at best maintain yield). A strategy of saving water at the field level simply to improve water productivity potentially threatens overall rice production. More rice with less water can only be achieved at the field level when water management is integrated with other crop and resource management practices to increase yield. Since technologies to reduce water inputs may have many negative impacts on weed infestation, nutrient availability, and labour and land productivity, they are not attractive to farmers unless suitable policies, an effective institutional organization, and legislation are available to promote their adoption. Under mild water-short conditions, the emerging aerobic rice system can potentially produce more rice with less water than flooded rice systems. However, special high-yielding aerobic rice varieties need to be bred, and a lot of research is still needed to develop sustainable and viable aerobic rice systems.

To produce more rice, field-level technologies have to be integrated with system-level management and technologies (such as water recycling, proper cropping scheduling, conjunctive use of groundwater) such that the water saved at the field level is used more effectively to irrigate previously un-irrigated or low-productivity lands. In many rice areas where there is already a high degree of recycling and conjunctive use of water, technologies to reduce outflows from the field may conflict with existing system-level technologies, and the amount of water that can be saved in the system could be far less than assumed from computations of field-level water savings. The impact of reducing water inputs for rice production on sustainability and environmental services of rice ecosystems warrants further investigation. Many of the measures to reduce water inputs and increase water productivity mentioned above come at a labour or financial cost and will not likely to be adapted by farmers in areas where farmers do not have to pay for irrigation water. Substitution of water for labour in irrigated rice is wide-spread and is likely to continue until irrigation water becomes more expensive.

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