Water saving in rice-wheat systems

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Abstract

Water shortage is a major constraint to sustaining and increasing the productivity of rice-wheat systems. Saving water can be elusive in that reducing seepage, percolation and runoff losses from fields does not necessarily save water if it can be recaptured at some other temporal or spatial scale, for example by groundwater pumping. Many technologies appear to save substantial amounts of water through reducing irrigation water requirement, but whether these are true water savings is uncertain as components of the water balance have not been quantified. Such technologies include laser levelling, direct drilling, raised beds, non-ponded rice culture and irrigation scheduling. It is questionable whether puddling saves water. Reducing non-beneficial evaporation losses is a true water saving, and optimal planting time of rice to avoid the period of highest evaporative demand and changing to non-ponded rice culture can save significant amounts of water. However, moving away from puddled, ponded to more aerobic rice culture sometimes brings new production problems. Furthermore, farmers faced with unreliable water supplies need to store water on their fields as insurance, and puddling assists retention of water during the rice crop. Rehabilitation and improvement of canal and power systems in Asia, funded by charging according to use, are required to facilitate adoption of many water saving technologies. Australian farmers pay fixed plus volumetric charges for water to cover the cost of infrastructure and operation of irrigation systems, which are continuously being improved to provide water on demand and minimise losses. They are able to plan their plantings based on knowledge of the likely amount of irrigation water available each season and crop water use requirement, and thus avoid wasting water and financial loss by overplanting and crop failure. Such approaches have the potential to increase production and water productivity in Asia, however the challenge would be to apply them in an equitable way that benefits many millions of subsistence farmers.

Media summary

The challenge for the 21st century is to grow more food using less water. Many promising technologies reduce irrigation water requirement, but whether many of them actually save water is unknown.

Keywords

Water use efficiency; evaporation; percolation; deep drainage; irrigation

Introduction

Rice-wheat systems are of immense importance for food security in South Asia and China, providing, for example, 85% of the total cereal production and 60% of the total calorie intake in India (Zheng 2000; Timsina and Connor 2001; Gupta et al. 2002). In South Asia, rice and wheat are grown in sequence annually on about 13.5 Mha in India (10 Mha), Pakistan (2 Mha), Nepal and Bangladesh, with about 85% of the RW area located in the Indo-Gangetic Plains (IGP). The area under RW systems in China was recently estimated to be 3.4 Mha (Dawe et al. 2004), considerably less than previous estimates of around 13 Mha. In China RW systems are concentrated along the Yangtse River valley from Sichuan province in the west to Jiangsu province in the east. The climate of RW regions in Asia is generally sub-tropical to warm temperate, with cool, dry winters and hot, wet summers.

The area and productivity of RW systems in the IGP increased dramatically between the 1960s and 1990s due to the introduction of improved varieties, increased use of fertilizers and other chemicals, and the expansion of irrigation. However, during the past decade, yields have stagnated or possibly declined, and there are large gaps between potential yields, experimental yields and farmers' yields (Gill 1999; Ladha et al. 2003). Therefore the sustainability of RW systems of the IGP and the ability to increase production in pace with population growth are major concerns. Symptoms of degradation of the resource base include declining soil organic matter content and nutrient availability, and increasing soil salinisation and weed, pathogen and pest populations. However, the biggest threat to sustaining or increasing the productivity of RW systems of South Asia and China is probably water shortage. Groundwater levels are declining rapidly in the NW IGP (Pingali and Shah 1999; Singh 2000), and water shortage during winter in Pakistan has been predicted to increase more than 4-fold by 2017 (Qutub and Nasiruddin 1994; Kahlown et al. 2002). Lack of irrigation and drainage infrastructure is a major constraint to increasing production in the eastern Gangetic Plains. Water scarcity is also a constraint to yield of the 0.7 Mha of RW/oilseed rape systems in the hilly country of Sichuan, China, and during early spring on the 2 Mha of RW/oilseed rape systems of the Sichuan basin. The availability of water for irrigation has declined dramatically in other RW regions of China (Hong et al. 2000).

Wheat is also grown in rotation with rice in southern NSW, Australia, a cool temperate region with hot, dry summers and low (average 30-40 mm every month, but highly variable) rainfall. Around 0.15 Mha of rice are grown each year, with the highest yields in the world, averaging 10.4 t/ha of paddy rice in 2003. Large areas of winter cereals (especially wheat) and a wide range of other summer and winter crops are grown in rotation with rice, but on a much less intensive scale than in the RW systems of South Asia and China. Wheat can be sown shortly after rice harvest, however by the time the wheat is harvested, it is too late to sow rice. Australian farmers are under great pressure to increase the water use efficiency of rice-based systems to remain profitable and avoid soil salinisation. In particular, profitability is threatened by decreasing water availability and certainty of supply, and increasing water price, as a result of environmental policies and the National Competition Policy (Humphreys and Robinson 2003). The sustainability of many regional communities is highly dependent on rice-based farming systems (Linnegar and Woodside 2003).

There are many contrasts between the RW systems of Asia and Australia, for example in terms of scale, climate, soils, rice cultural systems, mechanisation and regulation. Even some of the functions of water differ, apart from the essential functions of transpiration, solubilisation and transport of nutrients, and soil softening for root proliferation. For example, water is commonly applied in Asia to assist land preparation, puddling and transplanting, whereas water is only applied after land preparation is complete in Australia. Deep water (20-25 cm) is required in Australia during early pollen microspore to reduce cold damage (Williams and Angus 1994). All systems experience side-effects of water management on pest and disease populations, however the only common "cultural" function of water in both Asia and Australia is the ponding of water to assist weed control during establishment. But the urgent needs to reduce irrigation water use and increase water productivity, production and profitability are common to both.

What do we mean by "water saving" in RW cropping systems?

The term "water saving" has different meanings to different people. Real water saving occurs when losses that cannot be recaptured are reduced or eliminated, however the magnitude of any water saving can vary considerably depending on the spatial and temporal scales of interest (Seckler 1996; Loeve et al. 2002). Despite this complexity, the ultimate objectives of "water saving" are clear – to cease unsustainable overexploitation of surface and groundwater resources and increase the amount of water available for non-agricultural purposes (e.g. urban, environmental, recreational). Thus water saving in RW systems has the dual goals of using less water than is currently being used, while increasing production.

For a farmer, "water saving" is likely to mean using less **irrigation** water to grow a crop – ideally with the same or higher yield (or ultimately profit), thus increasing irrigation water productivity (g grain/kg irrigation water or $/kg irrigation water). However, saving irrigation water does not necessarily mean that total water use (from rain and soil water as well as irrigation) is reduced at the field scale – i.e. that water is really “saved”. While saving irrigation water *per se* has many benefits such as reducing costs to the farmer (e.g. pumping, water charges), increasing both yield and total water productivity (g grain/kg water from rain + irrigation + soil water) are required to meet the increasing demand for food, and to produce it from less water.

Saving water in cropping systems is ultimately about reducing non-beneficial losses – losses that can’t be economically recaptured elsewhere in the system. These non-beneficial losses are evaporation from the soil and irrigation water (as opposed to transpiration), and surface and deep drainage into waters too contaminated for reuse (e.g. saline groundwaters, the sea) or into locations from which it is too difficult to recapture (e.g. aquifers with low transmissivity).

Saving irrigation water for one crop in one field does not necessarily mean a net saving in irrigation or total water over time. For example, within a field, it may be possible to reduce the amount of irrigation and force a crop such as wheat to use more of the stored soil water while maintaining yield. However, this may also mean that a larger amount of irrigation water is required to refill the soil profile for the next crop, with no net irrigation or total water savings over the cropping system. Thus, in evaluating strategies for saving water it is important to consider the cropping system over time rather than individual crops in isolation.

Issues of scale are also extremely important (Molden 1997). For example, if deep and surface drainage can be captured and reused elsewhere at the spatial scale of interest, a reduction in drainage is not a water saving. Evaluation of the impact of irrigation water saving technologies at the field and farm scales on the availability of water at larger scales is complex and requires the use of approaches that integrate the effects over space and time, such as the 3-dimensional surface-groundwater interaction models developed by Khan et al. (2002a,b; 2003a) for the Rechna Doab basin in Pakistan and the lower Murrumbidgee basin in Australia.

This paper reviews methods for saving water and increasing water productivity at the field scale in RW systems in Asia and Australia. Much of this work has focussed on methods for saving **irrigation** water and increasing **irrigation** water productivity. In some cases the combined productivity of irrigation plus rain (“input water productivity”) was considered. However few studies have examined the impact on total water productivity, or whether savings in irrigation water at the field scale translate into true water savings at the field, cropping system or regional scales.

Increasing water productivity in RW fields

Water productivity can be increased by increasing yield and/or reducing water use. There have been substantial increases in irrigation and total water productivity of RW systems in Asia and Australia over the past thirty years, largely due to increased yields of both rice and wheat as a result of improved varieties and management of water, nutrients, weeds, pests and diseases (Hobbs and Gupta 2000; Hong et al. 2000; Ladha et al. 2000; Kahlown et al. 2002; Alam et al. 2003; Humphreys and Robinson 2003; Dawe 2004; Humphreys et al. 2004).

Approaches with the potential to further increase yield and thereby water productivity of RW systems of the IGP include laser land levelling, reduced tillage, raised beds, improved germplasm, site specific nutrient management, stubble mulching and integrated pest management (RWC-CIMMYT 2003a). In Australia yields will continue to increase through improved varieties (especially increased cold tolerance in rice and selection of wheats for irrigation), and improved rice establishment and soil and water management, aided by precision agriculture (Humphreys et al. 2003, 2004). Tuong et al. (2004) further discuss technologies for increasing water productivity in irrigated rice, and the need to address the complex interactions between water management and nutrients, weeds and environmental impacts.

Saving water in RW fields

Rice and wheat production are favoured by vastly different soil and water management and weather conditions. Therefore approaches to saving water can be quite different for the two crops, and strategies for saving water in one crop may impact positively or negatively on yield or water productivity of the following crop, and hence the total cropping system. For example, puddling to reduce percolation losses from rice may impair wheat performance. However, there are also generic approaches to saving water or increasing water productivity that can benefit both rice and wheat at the field scale, such as laser land levelling, drainage recycling systems, the ability to forecast rainfall and irrigation water availability, and improved reliability of water supply systems. While some water saving technologies decrease drainage losses without affecting evaporation, others predominantly affect evaporation, and many technologies affect both. Reduction in evaporation is likely to be a true water saving, whereas drainage can often be recaptured at some scale in the system. Therefore technologies that primarily affect deep drainage or evaporation losses are discussed separately, followed by technologies that affect both.

Reducing seepage and percolation losses in RW fields

Percolation or deep drainage loss is the vertical movement of water below the root zone where it cannot be recovered by crops, whereas seepage is lateral flow through bunds. Seepage and percolation losses at the field scale may be recaptured at a higher system scale, however recapture often comes at a cost in terms of energy for pumping, purchase of irrigation water and labour, construction of drainage systems, and greenhouse gas emissions associated with the production or use of energy. Seepage and percolation losses can be reduced by measures such as confining rice to less permeable soils, reducing ponding depth and alternate wetting and drying (AWD) irrigation for rice, laser levelling and raised beds. Puddling is also used to reduce percolation rate during the rice cropping period, but whether the total input of water is actually reduced and whether water is really saved are highly questionable (see below).

Soil type

Soil type has a large influence on irrigation water requirement due to much higher percolation losses on coarser textured soils. This is particularly true for rice grown under ponded or saturated conditions for most of the season. Seasonal percolation losses of 57-83% of the total input water are common in the NW IGP, with highest losses (up to 1,500 mm) on sandy and sandy loam soils, and lowest losses on loams and clay loams (up to 890 mm) (Prihar and Sandhu (1987) as cited in Hira and Khera 2000 p. 61; Tripathi 1996). As rice is a shallow-rooted crop, with the majority of roots in the top 20 cm, some of the water percolating beyond the root zone of rice is likely to be recaptured during the wheat phase, when roots can extract water up to depths of around 200 cm (Prihar et al. 1976, 1978a; Gajri and Prihar 1985; Humphreys et al. 2004). Therefore the percolation losses from rice in many studies probably overestimate the actual drainage losses below the root zone in RW systems. Nonetheless, deep drainage losses below the root zone of the RW system can still be very large. For example, assuming that after rice harvest the plant available water content of the profile in sandy loam and clay loam soils to a depth of 200 cm is 300 and 500 mm, respectively, and that this water is used by a subsequent wheat crop, then the deep drainage losses below the root zone of the RW system in the studies of Tripathi (1996) would range from 390 to 1,200 mm. Much of the RW area of the NW IGP is located on sandy loam to clay loam soils with infiltration rates up to 20 mm/day (Bhatti and Kijne 1992; Velayutham et al. 1999). In addition to the problem of high irrigation water requirement, excessive percolation from channels and fields on permeable soils has led to high watertables and problems of salinisation in substantial areas where groundwater quality is poor, such as in much of the RW area in Pakistan (especially in Sindh province) (Aslam 1998) and problems of waterlogging in south west Punjab, India (Hira and Khera 2000). In such regions the groundwater may not be suitable for reuse, for example in most areas of Sindh, and reducing percolation losses is a real water saving.

In contrast to the NW IGP, annual deep drainage from Australian rice fields is around 200 mm as farmers are tightly regulated to reduce percolation losses and thus watertable rise and secondary salinisation (Humphreys et al. 1994). Rice culture is restricted to soils with at least 2-3 m of continuous medium to heavy clay (i.e. >45% clay) in the top 3.5 m, and irrigation water use must not exceed a target set at the end of each rice season based on actual net evaporative demand. In addition, the total area of rice that is permitted on each farm each year is restricted, and rice area and water use are closely monitored by the farmer-owned irrigation companies. “Rice environmental policy” is defined and implemented by the irrigation companies as part of their overall Land and Water Management Plans. There is considerable variation in percolation rates across soil types and within fields (van der Lely and Talsma 1978; Beecher et al. 2002) and small highly permeable areas can make a large impact on total percolation losses (Tuong et al. 1994; Humphreys et al. 1998). Therefore there has been widespread adoption of recently developed electromagnetic (EM31) survey technology for rapidly, accurately and inexpensively identifying soil variability and assessing suitability from texture, or more accurately from soil sodicity, for rice fields, irrigation channels, drains and water storages (Beecher et al. 2002). To date approximately one-third of the rice region has been surveyed using EM31.

Puddling for rice

Most rice in Asia is transplanted into puddled soils. Puddling is done for a range of reasons including weed control, ease of field levelling and transplanting, and to reduce percolation losses. The relative importance ascribed to each of the above reasons varies. For example, Tabbal et al. (2002) consider that puddling in central Luzon, Philippines, is done primarily for weed control, whereas Kukal and Aggarwal (2003) and Gajri et al. (1992) place more emphasis on its role in reducing percolation losses in NW India, where soils are highly permeable. Puddling is not essential for rice growth and yield, with many studies (but not all e.g. Singh et al. 2001) reporting similar yields for transplanted or direct seeded rice with and without puddling (e.g. Aggarwal et al. 1995; Humphreys et al. 1996; Kukal and Aggarwal 2003). The high yielding rice cultural systems of Australia and California, USA, are not puddled.

Although it is widely recognised that puddling reduces percolation, there are surprisingly few reports of quantitative field comparisons of percolation losses in puddled and non-puddled soils. These indicate that the effect of puddling on percolation rate ranges from little to reductions from 30 to 13 mm/day on flooded sandy loam soils and from 17 to 3 mm/day on flooded clay soils (Wickham and Singh 1977; Sharma and De Datta 1985; Humphreys et al. 1992, 1996; Kukal and Aggarwal 2002).

Despite reducing percolation losses during the rice crop, puddling does not necessarily reduce the total water input for rice (Tuong et al. 1996; Guera et al. 1998; Tabbal et al. 2002). However, there are only a few reports on comparisons of total water use or percolation losses in puddled and non-puddled systems that include the whole period from pre-irrigation to harvest, and that use the same water management after planting. An exception was the study of Singh et al. (2001) which compared water use and yield of water seeded rice with and without puddling on a sandy loam at Delhi, with water depth maintained at 5 cm in both treatments. Averaged over three years there was an irrigation water saving of only 75 mm with puddling out of a total irrigation water application of 1,537 mm. Thus, even on this highly permeable soil, the irrigation water saving with puddling was relatively small in comparison with the total water use.

Puddling for rice induces high bulk density, high soil strength and low permeability in sub-surface layers (Sharma and DeDatta 1986; Aggarwal et al. 1995; Kukal and Aggarwal 2003), which can restrict root development and water and nutrient use from the soil profile for wheat after rice (Sur et al. 1981; Gajri et al. 1992). However the impact of puddling for rice on the performance of wheat after rice is variable across sites and years (Table 1; Sharma et al. 2003). Sharma et al. (2003) noted that the few negative yield trends for wheat in long term experiments (Ladha et al. 2003) were mostly observed in medium- to fine-textured soils, which undergo more radical changes in soil physical properties during puddling, while yield trends were positive on the coarse-texture soils of Punjab and Haryana. However results from field experiments show no clear relationship with soil type (Table 1). The results may be confounded by site history – if a site has a history of puddling and a compacted layer prior to the commencement of rice tillage treatments then the initial site conditions may prevent any wheat response to rice tillage treatments. Unfortunately few studies evaluating the impact of puddling for rice on wheat performance report site history or soil physical properties prior to the imposition of the treatments. The findings of Aggarwal et al. (1995) and Kukal and Aggarwal (2003) showed that the effects of puddling on soil physical properties increase with puddling intensity, depth and history of puddling, and that it may take one to several years before this significantly affects the performance of wheat when starting with a soil with no puddling history or compacted layer.

Reducing evaporation losses in RW fields

Reducing non-beneficial evaporation direct from the soil or free water lying on the field is a true water saving, although it may be countered to some degree by increased transpiration rates as a result of impacts on the microclimate experienced by the plant. The size of this effect has not been established. Evaporation from the free water surface accounted for 40% of the total evaporative loss from continuously flooded water seeded rice in southern Australia (Simpson et al. 1992). Technologies that reduce the extent or duration of free water or surface soil saturation include alternate wetting and drying of rice fields instead of continuous ponding, raised beds with furrow irrigation, laser land levelling, and drip and sprinkler irrigation. Evaporation from the soil surface can be reduced by mulching, by changing the time of crop establishment to coincide with periods of lower evaporative demand, and by faster turn around between crops through direct drilling to use residual surface soil water and perhaps save an irrigation.

Table 1. Effect of puddling and compaction for rice on yield of wheat after rice

Location/Country	Soil	Site history	Effect of puddling on wheat yield	Reference
Punjab, India	Sandy loam	Non-rice (cotton-wheat, sugar cane, maize-wheat)	Increased - year 1	Singh 1998
			Decreased - year 2	
Punjab, India	Silty clay loam	Rice-wheat for last >20 years	Increased - year 1	
			None - year 2	
Punjab, India	Sandy loam *1, 2 & 4 pass pudding*	Non-rice for last >20 years (maize/pearl millet-wheat)	None – year 1 Decreased – years 2-5 with 4 passes compared with 2 or 1 pass puddling	Aggarwal et al., 1995
Punjab, India	Sandy loam *Rice-wheat cf. maize wheat*	Non-rice (maize-wheat)	Decreased after rice cf after maize	Boparai et al., 1992
Punjab, India	Sandy loam	Non-rice	Decreased	Meelu et al. 1979; Sur et al. 1981
Punjab, Uttar Pradesh, India Haryana	Sandy loam Silty clay loam	Rice-wheat for last 9-10 years Rice-wheat for last >20 years	None – year 1 None – year 1	Sidhu 2003
Punjab	Loamy sand	Non-rice	None – year 1	
Punjab	Sandy loam	Non-rice	None – year 1	
Punjab	Silty clay loam	Rice-wheat for last 9-10 years	None – year 1	
Uttar Pradesh	Sandy loam	Rice-wheat for last 9-10 years	Decreased – year 1	
Punjab, India		Non-rice for last >20 years	No effect years 1&2 Decreased with normal (“deep” 10-12 cm) puddling in 3rd year	Kukal and Aggarwal 2003
Bhairahawa, Nepal	Silty clay loam	?	Decreased	Hobbs et al. 2002
	Silty loam	?	Decreased	
Pantnagar, India	Sandy laom	?	None over 6 years	
Coleambally, Australia	Clay	Rice-wheat-grazed pasture; never puddled	None – 1 & 2 years puddling	Humphreys et al. 1996
	Clay loam	Rice-wheat-grazed pasture; never puddled	None – 1 year puddling	

Adapted and updated from Connor et al. (2002)

Sowing/planting date

In NW India the evapotranspiration requirement of rice declines from around 800 to 550 mm as the date of transplanting is delayed from 1 May to June 30 (Hira 1994a in Hira and Khera 2000 p. 57). Substantial irrigation water savings (25-30% or 720 mm) can be achieved by delaying transplanting from mid-May to mid-June (Narang and Gulati 1995). Therefore the recommended practice in NW India is to transplant around mid-June. However, many farmers plant earlier than this (e.g. 57% in Punjab) because of external factors such as increased pest pressure on later planted crops and availability of labour and canal water or electricity for pumping (Hira and Khera 2000; Gajri et al. 2002). Mechanical transplanting could potentially reduce the need for earlier transplanting, but the cost of mechanical transplanters is prohibitive and requires specialized training in seedling production on mats, knowledge of sedimentation rates for different soil types to avoid seedling burial and good land levelling. Direct seeding could help overcome the problem of labour availability, however the optimum sowing date may need to be earlier than the optimum transplanting date which could increase the crop water use requirement. It is not clear if changing to direct seeding will increase or reduce the water requirement for rice, and the impact may vary depending on sites and systems (Dawe 2004). Although delayed rice planting can save water, it can also delay planting of wheat beyond the optimal time, causing yield loss of 1-1.5% per day due to grain filling at higher temperatures (Prihar and Grewal 1988; Ortiz-Monasterio et al. 1994).

While delaying transplanting in the NW IGP to the optimum time saves water, bringing forward transplanting in eastern India enables more productive use of rainfall. Here, irrigation water is scarce, and the need for irrigation can be avoided and total system productivity increased by establishing rice with rainfall supplemented by irrigation from groundwater during the pre-monsoon period, and by raising bund height to 20 cm to capture rainfall (Gupta et al. 2002). This also benefits the subsequent wheat crop due to the opportunity for earlier planting.

Varietal duration

Water can also be saved by using varieties of shorter duration; however, this may come at the expense of yield. For the Australian situation, Reinke et al. (1994) argued that reducing duration could save up to 10% of irrigation water, whereas Williams et al. (1999) concluded that reduced duration will always reduce yield potential and hence water productivity. While there is some evidence for the latter argument, varieties with higher yield potential and shorter duration have been developed (Reinke et al. 2004). Short duration varieties also facilitate increased water use efficiency of the farming system. For example, earlier maturity allows earlier harvest, increasing the chance of timely establishment of a winter crop after rice and making more efficient use of stored soil water and winter rainfall instead of losing it as deep and surface drainage or transpiration by weeds.

Mulching

The few reports on the effect of mulching on water use in RW systems refer to mulching of wheat, and suggest tha t sufficient water is saved (25-100 mm) to reduce the number of irrigations by one or irrigation time by an average of 17%, or to increase yield in water limiting situations (Zaman and Choudhuri 1995; OFWM 2002; RWC-CIMMYT 2003b). Surface seeding and dibbling of wheat followed by mulching with rice straw (4-6 t/ha) are practised on about 60% of the RW system in the Sichuan Basin of China. The time between rice harvest and wheat sowing is relatively long (60-85 days), and spreading the rice straw mulch immediately after harvest is currently being explored as a technique to control weeds and reduce evaporation. This technique is more attractive where farmers are growing oilseed rape after rice as they can broadcast the seeds which are small enough to fall through the mulch to the soil surface. Surface seeding of wheat and straw mulching is also practised by a few farmers in the Terai of Nepal and in eastern Uttar Pradesh and Bihar, India.

Mulching is not commonly practised in RW systems in South Asia or Australia, as sowing into stubble is problematical in mechanised culture due to clogging of the machinery with loose straw and "hair-pinning" (the straw bends but is not cut or buried, resulting in seed remaining on the surface). Efforts are underway to develop direct drilling and stubble mulching machinery to overcome this problem (RWC 2002). A novel, promising approach recently developed and tested by Australian and Indian collaborators is the "Happy Seeder", which combines the stubble mulching and seed drilling functions into the one machine (Blackwell et al. 2004). The stubble is cut and picked up in front of the sowing tynes (which therefore engage bare soil) and deposited behind the seed drill as a mulch. This concept is also being tried in Pakistan, having 'imported' the idea from India. Results to date from India suggest that wheat can emerge through 8 t/ha of evenly spread rice straw mulch with no detrimental affect, although 4-6 t/ha is considered optimum in Sichuan, China. Adapting the technology to the Australian situation with rice stubbles of 10-14 t/ha will be a challenge.

In central and NW India and Pakistan, a very hot dry period occurs for about two months between wheat harvest and rice planting, during which the fields are bare fallow and evaporative demand is very high. The magnitude of the soil water loss by evaporation, and the potential for stubble retention or mulching to reduce non-productive evaporative losses during this period, have not been explored. The most efficient and practical strategy is likely to be irrigation management of the wheat to use stored water after rice and achieve dry down of the soil profile by the time of wheat harvest rather than use of mulches to prevent losses after harvest. The majority of the wheat straw is harvested for animal fodder (Gajri et al. 2002).

There are few reports of evaluation of mulching for rice, apart from those from China, where considerable input water savings of 20-90% (140-2,400 mm) occurred with plastic and straw mulches in combination with aerobic culture compared with continuously flooded transplanted rice (Lin et al. 2002; Shen and Xu 2003; Pan et al. 2003). Much of the water savings was probably due to higher percolation losses in the flooded systems (Lin et al. 2002).

Reducing seepage, percolation and evaporation losses in RW fields

There are many technologies which appear to save water in RW systems through a combination of reduced seepage, percolation and evaporation losses; however, separation of these components has seldom been attempted. Some practices that impact on all three are discussed here.

Land levelling and layout

The extent of laser levelling in South Asia and China is currently extremely small, compared with 50-80% of the rice land in Australian rice-based systems (Humphreys and Bhuiyan 2001; Lacy and Wilkins 2003).

Land levelling can reduce evaporation and percolation losses from wheat by enabling faster irrigation times and by eliminating depressions and therefore ponding of water in depressions. This also reduces waterlogging problems, especially on heavy textured soils. Laser levelling in Pakistan resulted in average wheat irrigation water savings of 25% in comparison with non-lasered fields while increasing yield by 20-35% and reducing labour and land preparation costs (Kahlown et al. 2002; OFWM 2002; Alam et al. 2003).

Land levelling also reduces the depth of water required to cover the highest parts of the field and for ponding for weed control in rice, and therefore percolation losses, more so on more permeable soils. Rickman (2002) found that rice yields in rainfed lowland laser-levelled fields were 24% higher than in non-lasered fields in Cambodia, and that yield increased with the uniformity of levelling.

Water management for rice

There are numerous reports of large irrigation water savings when changing from continuously flooded rice to saturated soil culture to alternate wetting and drying, but yields decrease as soil water content declines below saturation (Sandhu et al. 1980; Heenan and Thompson 1984, 1985; Xu 1999; Bouman and Tuong 2001; Bouman et al. 2002). However, many studies throughout India and China have shown that continuous ponding is not necessary to maintain rice yields at reasonable levels (Sandhu et al. 1980; Prihar and Sandhu 1987 p. 66 in Hira and Khera 2000; Chaudhary 1997; Xu 1999; Belder et al. 2004; Tuong et al. 2004).

Results from NW India consistently show substantial irrigation water savings (24-40% or up to 650 mm) with no or small yield loss, and even a yield increase on a sodic soil, in changing from continuous submergence to irrigating 1 to 3 days after the floodwater has disappeared (Sandhu et al. 1980; Chaudhary 1997; Sharma 1999). Sandhu et al. (1982) also showed that about 60 mm of irrigation water can be saved, while maintaining yield, by cutting off irrigation 1 week earlier (about 2 weeks before harvest) on a sandy loam. Therefore the recommended practice in Punjab, India is to irrigate 2 days after the water has disappeared and to cease irrigating about two weeks before harvest. Sharma (1989) found no effect on rice yield and a water saving of 843 mm (23%) by allowing the soil to dry to -10 kPa at 10 cm depth prior to reflooding for periods of 1-3 weeks. Hira et al. (2002) compared the recommended practice with irrigation at soil matric potentials of -8 to -16 kPa at 15-20 cm depth. The number of irrigations was highest with the recommended practice (29, at 50 mm per irrigation) declining to 18 irrigations when matric potential reached –16 kPa, an irrigation water saving of 550 mm with no effect on yield.

Much of the irrigation water saving with reduced water depth in Asia is probably due to reduced percolation losses, and therefore may not be a real saving. Kukal and Aggarwal (2002) showed that percolation rate declined rapidly from about 15 to 5-10 mm/day as water depth declined from 100 to 60 mm on a puddled sandy loam, and from 35 to less than 20 mm/day as the water depth declined from 100 to around 20 mm without puddling.

Bouman and Tuong (2001) concluded that the most promising option to save irrigation water and increase input (irrigation plus rain) water productivity without too much effect on yield was by reducing the ponded water depth from 5-10 cm to the level of soil saturation. In practice this means shallow flooding and frequent irrigation to re-flood the field once the floodwater disappears, and requires timely and accurate water delivery to fields. Bouman and Tuong (2001) suggested that most Asian farmers in public irrigation systems have little incentive to reduce water input to their fields since irrigation water is mostly charged on an area basis, and irrigation systems would need to be able to supply water on demand. They considered that farmers operating pumps would be likely to benefit most from this water saving technique. However, while the cost of electricity for pumping is subsidised, and where power supply is unreliable and only available for short periods, as in NW India, then farmers will continue to apply deep water to their fields as insurance.

In Australia, ponding water for 2-3 hours (sufficient time to saturate the rootzone) every 7 days throughout the season reduced irrigation water use by 60%, but yields were very low (1-2 t ha^{-1} compared with 9 t ha^{-1} for conventional management) and grain quality was unacceptable (Heenan and Thompson 1984, 1985). Delayed flooding (intermittent irrigation every 7 days with continuous ponding commencing about 2 weeks prior to panicle initiation) enabled maintenance of both yield and grain quality, with irrigation water savings of around 25% due to reduced percolation losses. However, this work was carried out on a relatively permeable soil, therefore the reported water savings may overestimate what can be achieved on more typical Australian rice soils. Delayed flooding is currently being re-evaluated using modern semi-dwarf varieties on less permeable soils, and indications are that irrigation water savings of about 15% can be achieved with no effect on yield (Thompson, unpubl. data).

The requirement for deep water protection from low temperatures during the early pollen microspore stage currently limits the scope for saving water by moving away from ponded rice culture in Australia without a substantial yield penalty. Furthermore, during the period from panicle initiation to flowering, crop growth rates are as high as 250-300 kg/ha/d with potential evapotranspiration frequently in excess of 10 mm d^{-1}; thus the risk of water deficit stress during this period is likely to be high with non-ponded culture. The degree of soil water depletion that the rice crop can experience without losing yield in the south east Australian rice growing environment is currently unknown. In the heavy clay soils used for rice growing, most roots are in the top 10 cm (Heenan and Thompson 1984), therefore available soil water is limited and the crop could quickly experience water deficit during the reproductive stage if not continuously flooded. Thus, incorporation of sufficient cold tolerance into Australian rice cultivars to obviate the need for deep water for cold protection would also need to be accompanied by incorporation of deeper rooting characteristics to reduce the possibility of water deficit in a non-ponded system.

Aerobic rice. Aerobic rice cultivation is a new technology that involves the use of varieties bred to provide higher yield potential with a much lower water input than required for traditional rice cultivation. Aspects of the technology are discussed in detail in several papers in Bouman et al. (2002), and by Tuong et al. (2004). Compared with traditional lowland rice production, aerobic systems using aerobic cultivars in China currently yield about 30% less, but with input water savings of about 60% (Wang et al. 2002), and to date aerobic cultivars have only been developed for environments in China and Brazil. There is evidence that yields of these cultivars decline dramatically after 3 to 4 years of mono-cropping and farmers in northern China are now advised not to continuously grow aerobic cultivars on the same land until the problem is better understood and manageable.

Changing from continuously flooded rice culture to more aerobic culture including alternate wetting and drying (AWD) on flats, furrow irrigated beds and aerobic rice culture has implications for other aspects of the rice production system, including control of weeds, nutrients and environmental impacts (Tuong et al. 2004). It may also have implications for nutrient management of rice crops grown in rotation with rice due to the effect of prolonged waterlogging on availability of nutrients during the rice and aerobic phases, especially phosphorus and iron (Willett 1982; Muirhead and Humphreys 1996). However, at the end of the rice phase with AWD, soil water content of the root zone for wheat is unlikely to be very different from that in continuously flooded culture as non-ponded rice is irrigated frequently to keep the soil water content near saturation, but this is yet to be confirmed.

Irrigation scheduling for wheat

Irrigation of wheat after rice should be scheduled to maximise use of stored soil water and winter rain while maintaining yield. Prihar et al. (1974, 1976, 1978a) established guidelines for irrigation scheduling for wheat on the coarse textured soils of northwest India. This work was done in soils without a restricting layer, commonly with maize as the previous crop, rather than the RW situation where there is often a dense layer at about 20 cm (Aggarwal et al. 1985; Kukal and Aggarwal 2003). Prihar et al. (1978b) concluded that wheat should be irrigated at around 60 and 70% depletion of plant available soil water storage to avoid yield loss, with the lower value for the lighter soil, compared with a deficit of 50% determined by Singh and Malik (1983) on a sandy loam in Haryana. The recommended practice involves one irrigation prior to soil preparation, an irrigation (~70 mm) at the crown (nodal) root initiation stage, 3-4 weeks after sowing, then a 70 mm irrigation whenever cumulative pan evaporation minus rain reaches 93 mm (an "IW/Pan" ratio of 0.75), with the last irrigation no later than mid-March for crops "sown on time". This method saved up to 160 mm of irrigation water compared with applying 70 mm at each of 5 key stages. However, translating this into practice for a farmer with no knowledge of pan evaporation is difficult, and published guidelines for farmers are based on prescribed intervals between irrigations according to sowing date, with some adjustments for light and heavy soils but no adjustments for seasonal weather conditions (PAU 2002). Narang and Gulati (1995) suggested that there was scope to reduce wheat irrigations further by publicising data from evaporation and rainfall and training farmers to keep their own evaporation-rain budgets. In the rice-based region of Australia daily potential evaporation for the last 7 days is publicised each night on regional television and in local newspapers. It can also be acquired by phone or from the internet. A simple wheat irrigation scheduling software package SIRAGCROP was developed in the 1980s and used by a few farmers (Stapper et al. 1988). There have been no further developments in irrigation scheduling software for wheat in rice-based systems since then, although there is some farmer interest.

Irrigation method

Pressurised irrigation systems (sprinkler, surface and subsurface drip) have the potential to increase irrigation water use efficiency by providing water to match crop requirements, reducing runoff and deep drainage losses, and generally keeping the soil drier reducing soil evaporation and increasing the capacity to capture rainfall (Camp 1998). There are few reports of the evaluation of these technologies in RW systems. In Australia sprinkler irrigation of rice to replace evaporative loss reduced irrigation water use by 30-70% (Humphreys et al. 1989), however, even at frequencies of up to 3 times per week, yield declines of 35-70% occurred (Muirhead et al. 1989). Irrigation water use was reduced by about 200 mm in rice with subsurface drip commencing two weeks prior to panicle initiation compared with conventional flooded rice culture; however, yields with drip also decreased and there was no increase in irrigation water productivity (Beecher et al. 2004). Little is known about how to manage potentially more efficient but highly expensive irrigation systems to achieve high yields and save water for RW systems. Such systems are only likely to be economic with diversification into higher value crops, which becomes more feasible with the introduction of raised beds.

Raised beds

The use of raised beds for the production of irrigated non-rice crops was pioneered in the heavy clay soils of the rice growing region in Australia in the late 1970s (Maynard 1991), and for irrigated wheat in the RW areas of the IGP during the 1990s, inspired by the success of beds for wheat-maize systems in Mexico (Meisner et al. 1992; Sayre and Hobbs 2004). Potential agronomic advantages of beds include improved soil structure due to reduced compaction through controlled trafficking, and reduced waterlogging and timelier machinery operations due to better surface drainage. In the IGP beds also create the opportunity for mechanical weed control and improved fertiliser placement. In RW systems in Asia and Australia permanent beds also provide the opportunity for diversification to waterlogging sensitive crops not suited to conventional flat layouts, and the ability to respond rapidly to market opportunities. While the potential benefits of beds for wheat production in the IGP have been known for some time (Dhillon et al. 2000), evaluation of beds for rice and permanent beds in RW systems commenced more recently (Connor et al. 2002).

Farmer and researcher trials in the IGP suggest irrigation water savings of 12 to 60% for direct seeded (DSRB) and transplanted (TRB) rice on beds, with similar or lower yields for TRB compared with puddled flooded transplanted rice (PTR), and usually slightly lower yields with DSRB (Gupta et al. 2002; Jehangir et al. 2002; Balasubramanian et al. 2003; Hossain et al. 2003; Khan et al. 2003; OFWM 2003). However many studies in the NW IGP show little effect of rice on beds on water productivity (typically around 0.30-0.35 g/kg) as the decline in water input was accompanied by a similar decline in yield

(Sharma et al. 2002; Singh et al. 2002; Jehangir et al. 2002; OFWM 2002). The causes of reduced rice yield include increased weeds and nematodes, sub-optimal sowing depth due to lack of precision, and micronutrient (iron, zinc) deficiencies.

There appears to be little scope for saving irrigation water with furrow irrigated rice on beds on the heavy clay soils of southern Australia. Investigations over four growing seasons showed irrigation water savings of around 10% with saturated soil culture (water continuously in the furrows), with a similar reduction in grain yield (Thompson et al. 2003). Irrigation water use of rice grown on beds with intermittent irrigation until two weeks before panicle initiation, followed by continuous flooding, was similar to water use of dry-seeded rice on the flat with continuous flooding commencing about one month after sowing (Beecher et al. 2004). This is in contrast with findings on a more permeable soil in semi-tropical southern Queensland where irrigation water use of rice on beds with saturated soil culture was 32% less than flooded rice on the flat due to reduced percolation losses, which were considerable (Borrell et al. 1997). Studies in the USA have also shown considerable water savings with furrow irrigated rice on beds (Tracy et al. 1993; Vories et al. 2002).

There are several reports of reduced irrigation amounts or time, with similar or higher yields, for wheat on beds compared with conventional tilled wheat, from farmer participatory trials and researcher plots across the IGP. Typical irrigation savings range from 18% to 30-50% (Hossain et al. 2001; OFWM 2002; Talukder et al. 2002; RWC-CIMMYT 2003a,b; Hobbs and Gupta 2003b; Khan et al. 2003). In contrast, on a marginally sodic silt loam in NW India, Sharma et al. (2002) found a 20% yield reduction for wheat on beds irrigated when soil matric potential at 20 cm reached –50 kPa, with only 20 mm saving in irrigation water use compared with conventionally tilled wheat. In Punjab, yields of wheat on beds and flats were similar on two loam soils, but lower on the beds on a sandy loam in a year with unusually low radiation in January (Humphreys et al. 2004). The wheat on the sandy loam appeared to suffer from water deficit stress prior to the first irrigation, impairing tillering, and demonstrating the need for refinement of irrigation scheduling guidelines for bed layouts. Direct drilled barley and wheat on raised beds produced 26% more grain (range 18-43%) than on the flat over four years on heavy clay soils also used for rice growing in Australia (Thompson and North 1994), with similar increases in irrigation water productivity. The better performance on beds was considered to be due to reduced waterlogging. In northern China, irrigation water applications were reduced by an average of 17% for wheat on beds, while grain yields were increased by in excess of 10%, due to improved soil physical properties, reduced lodging and decreased incidence of disease (Wang et al. 2004).

Direct seeding

Input water savings of 35-57% have been reported for dry seeded rice sown into non-puddled soil with the soil kept near saturation or field capacity compared with continuously flooded (~5 cm) PTR in research experiments in NW India (Singh et al. 2002; Sharma et al. 2002). However yields were reduced by similar amounts due to iron or zinc deficiency and increased incidence of nematodes. In contrast with the results of small plot replicated experiments, the results of participatory trials in farmers' fields in NW India and Punjab's Pakistan suggest a small increase or 10% decline in yield of DSR on the flat compared with puddled transplanted rice, and around 20% reduction in irrigation time or water use (Gupta et al. 2002; Qureshi et al. 2003), increasing water productivity.

Farmer and researcher experience with direct drilling of wheat in Haryana, NW India, and Punjab, Pakistan indicates irrigation water savings of 20-35% or 90-100 mm compared with conventional tillage, with the largest savings in the first irrigations, and comparable or higher yields due to earlier sowing (OFWM 2002; Hobbs and Gupta 2003a; RWC-CIMMYT 2003b). Factors contributing to the saving in irrigation water probably include faster flow across the non-tilled fields, no loss of surface moisture as occurs with cultivation, the ability to sow earlier and take advantage of residual soil moisture and create storage capacity to capture winter rain, and the opportunity to finish the wheat crop in a period of lower evaporative demand. On heavier soils direct drilling may even eliminate the need for a pre- or post-sowing irrigation in the IGP (Hobbs and Gupta 2003b), as in Australian RW systems. In contrast with the results of the farmer trials in the IGP, Gajri et al. (1992) found lower yields of direct drilled wheat compared with conventionally or deep tilled wheat over three consecutive years on a sandy loam. Tillage resulted in deeper and denser rooting and increased transpirational and N use efficiency. For a given yield level, higher inputs of irrigation water and N were required with direct drilling compared with conventional tillage.

The area of direct drilled or zero tilled wheat after rice in northwest India and Pakistan has expanded rapidly since 1998/9, exceeding 0.3 Mha in 2001/2 (Hobbs and Gupta 2003a), 0.5 Mha in 2002/3 and 1.1 Mha in 2003/4 (RWC 2004). Direct drilling is also practised on the Chengdu Plain of China by dibbling or surface seeding and mulching with rice straw. Direct drilling is the predominant method for establishment of wheat after rice in Australia, although it is only practised on a proportion (5-39% depending on location) of the rice fields each year (Humphreys and Bhuiyan 2001). In both Australia and the NW IGP, rice stubble is normally burnt, or sometimes just the loose straw is burnt, prior to drilling. In contrast, in the Sichuan Basin of China, it is the wheat straw is burnt. Air pollution from stubble burning is a serious problem in both the NW IGP and the Sichuan Basin.

In Australia, rice fields are most commonly left fallow after harvest until establishment of the next rice crop 5-6 months later, or wheat or some other winter crop about 12 months later. Establishment of wheat immediately after rice increases water use efficiency of the system by using up the stored soil water and creating capacity in the soil to capture and use winter rainfall which would otherwise by lost by surface runoff, transpiration by weeds, or deep drainage. Depending on irrigation management and watertable depth and salinity, crop water use from upflow from the watertable can also be a significant source of water. Crop water use from the watertable was 28% of the total crop water use on a loam soil, and 15% on a clay loam with a poorly structured heavy clay subsoil, for well-irrigated wheat with a fresh (1 dS/m) watertable at 1 m (Meyer et al. 1987, 1990).

Improving water supply systems

Unreliable water supply and cheap water (or power for pumping water) are major constraints to the adoption of many potential water saving technologies which require more timely and controlled water management.

The canal irrigation system in Punjab, India irrigated 1.67 Mha in 1990/91, and this has declined to 0.99 Mha in 2001/2 due to deterioration in the system, forcing farmers to increasingly rely on groundwater and exacerbating the depletion of groundwater resources (The World Bank 2003). The World Bank report recommends removal of subsidies on surface water supplies and electricity to generate funds to rehabilitate the canal and power supply systems. More reliable canal and power systems would then enable adoption of many water management practices with the potential to save water and increase water uctivity. The irrigation companies supplying surface water to Australian rice-based systems have all been privatised with local ownership by the farmers, who pay both fixed and volumetric prices for irrigation water to cover capital, maintenance and operating costs (Humphreys and Robinson 2003). These companies invest considerable resources in automation of water ordering (by telephone), flow itoring and control of flow structures in channels and onto farms, and channel sealing, to provide water to farmers in a more timely and reliable manner, and to reduce system losses.

In the canal water distribution systems of north west India and Pakistan, there is often a gap between head and tail farm gate supply (Tyagi et al. 2004). Farmers at the tail end are often heavily reliant on the use of moderately saline groundwater to makeup the shortfall of the canal supply, resulting in lower yields of rice and wheat and lower water productivity due to salinisation. Tyagi et al. (2004) suggested that transfer of good quality groundwater from head to tail reaches by introducing water marketing would assist in increasing yields and water productivity in the lower reaches.

Forecasting weather and irrigation water availability

The ability to plan forward based on knowledge of likely irrigation water availability and rainfall and yield/water management relationships can increase water productivity and total production and reduce waste of water. Farmers in Asia currently plant crops in the hope of receiving enough irrigation water and rain for the planted area. Where crops fail or yield poorly due to over planting in relation to water availability, the water used to grow those crops has been wasted. Ahmad et al. (2004) found that rainfall variability was the main factor inducing temporal changes in water productivity in Pakistan’s Punjab. They identified the need for better forecasting of climatic conditions and adoption of appropriate water management strategies to sustain or increase water productivity. Australian irrigators have an access licence which provides them with a specified share of the available water in the surface or groundwater source. Each season they plan their plantings based on a regional irrigation allocation (% of the share that can be accessed) announced before the start of the irrigation season. The allocation is based on the amount of water in the dams and historic rainfall statistics, and may increase over time depending on rainfall in the catchment. Considerable progress has recently been made in the development of user-friendly software to enable farmers to predict the allocation at some future time from the current allocation, based on historic data and relationships between dam inflows and sea surface temperature (Khan et al. 2003b,c).

Conclusions

Saving water in RW systems can be elusive in that reducing seepage, percolation and runoff losses at the field scale does not necessarily save water if it can be recaptured again at some other temporal or spatial scale. Reducing non-beneficial evaporation losses from the soil or irrigation water is a true water saving, and optimal sowing/planting time of rice to avoid the period of highest evaporative demand can save significant amounts of water in the NW IGP. Mulching can also help reduce evaporative loss, and the effect of mulching needs further quantification. Promising technologies for direct drilling into stubble and mulching are currently under development and evaluation.

Many technologies appear to save substantial amounts of water in RW systems, but whether these are true water savings is not clear as components of the water balance have not been quantified. Such technologies include laser levelling, direct drilling, raised beds, non-ponded rice culture and irrigation scheduling of wheat.

Many of the soils used for rice culture in the NW IGP are highly permeable and their use for ponded rice culture is questionable because of their high irrigation requirement and associated leaching losses and groundwater pollution. However, moving away from ponded to aerobic rice culture (such as beds) on these soils sometimes brings a suite of new problems including weeds, micronutrient deficiencies, pests, and diseases.

Puddling reduces percolation losses during the rice cropping phase, however the amount of water used for soaking and puddling can be considerable, and it is questionable whether irrigation water is really saved. However, for farmers without an assured supply of water or power to pump water, the more important factor may be the ability to pond water on the field once the crop is planted, rather than the total amount of irrigation water used. Puddling can be detrimental to the yield and water productivity of wheat after rice; however, the reported findings are inconsistent, and may be confounded by failure to take into account site history or soil physical conditions prior to the start of experiments when examining the impact of tillage for rice on wheat performance.

Many studies in Asia show very large savings in irrigation water when moving away from continuously ponded rice culture to saturated soil culture, alternate wetting and drying with shallow irrigations, and furrow irrigated beds. The nature of the savings needs to be quantified to determine how much is a real water saving. However, farmers faced with unreliable water supplies have no choice but to store water on their fields as insurance against not being able to get water when they next need it. In contrast to the situation in the IGP, there is little scope for saving irrigation water with raised beds in Australian rice-based systems as deep drainage losses are already low due to the low permeability of the soils used for rice.

Australian irrigators are able to plan their plantings based on knowledge of the likely amount of irrigation water available each season, and crop water use requirement, and thus reduce wasting water by overplanting and crop failure. Adoption of such approaches in Asia has the potential to increase production and water productivity, however the challenge would be to apply them in a way that all the many millions of subsistence farmers affected benefitted equitably.

Our best bets for achieving substantial, real water savings in RW systems in Asia are laser levelling, shallow intermittent irrigation for rice, rice planting at the optimum time to reduce crop water use requirement, and direct drilling and mulching of wheat. The technologies to do this already exist, although it will take time for the adoption of laser levelling and direct drilling due to the need for additional machinery. However the necessary infrastructure to ensure the availability of water on demand to allow intermittent irrigation for rice is generally lacking in the IGP. Charging for power or water according to use and without subsidies would encourage better water management and generate funds to improve power and water supply systems, but the political will to achieve this may be lacking. Other technologies such as permanent beds and improved guidelines for irrigation scheduling require further evaluation and development.

Acknowledgements

We thank the Australian Centre for International Agricultural Research for financial support of research in rice-wheat cropping systems.

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