Effect of Crop Establishment Method and Irrigation Schedule on Productivity and Water Use of Rice

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A thesis by **prior publications** submitted to The University of Adelaide, South Australia

In the fulfilment of the degree of DOCTOR OF PHILOSOPHY

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ABSTRACT

Management strategies that reduce ground water depletion and labour requirement, while maintaining yield are urgently needed in north-west India where ground water table is declining at an alarming rate. Dry seeded rice (DSR) has been proposed as one means of achieving these objectives, but optimal water management for DSR is not well understood. Therefore field experiments were conducted to investigate the effects of irrigation scheduling on water balance and land and water productivity of DSR relative to the current practice of puddle transplanted rice (PTR). The irrigation scheduling was based on soil water tension (SWT) ranging from continuous flooding (CF)/daily irrigation to alternate wetting and drying (AWD) at SWT thresholds of 20, 40 and 70 kPa. Data from the field experiments were used to parameterise and evaluate the ORYZA2000 rice crop model which was then used to evaluate establishment method x water management practices.

Grain yield of DSR and PTR was similar (6.6-7.4 t ha^{-1}) when irrigation was scheduled daily or at 20 kPa. Yield of both PTR and DSR declined under higher water deficit stress (40 and 70 kPa irrigation thresholds), but to a greater extent in DSR, and more so in the drier year possibly due to severe iron deficiency. There was a large reduction (47-82%) in irrigation water input with irrigation at 20 kPa compared to daily irrigation in both crop establishment methods. Irrigation water use in DSR-AWD treatments was significantly lower than in respective PTR treatments (e.g. by 33–53% when irrigation was scheduled at 20 kPa). Maximum irrigation water productivity (WP_I) was obtained with 20 kPa SWT threshold, and was much higher for DSR (1.46 g kg^{-1}) than PTR (0.85 g kg^{-1}). Water productivity with respect to ET (WP_{ET}) was also highest with the 20 kPa threshold, with similar values (1.18 g kg^{-1}) for DSR and PTR. In both establishment methods, regardless of irrigation threshold, water saving was mainly due to reduced deep drainage, seepage and runoff.

ORYZA2000 predicted crop growth and yield well for CF and the 20 kPa irrigation threshold for both crop establishment methods, but predictions were sub-optimal for some parameters for PTR at higher irrigation thresholds. Model performance was unsatisfactory for DSR at thresholds >20 kPa, at least partly because of iron deficiency, which is not simulated by ORYZA2000. Based on the weather data for 40 rice seasons, the predicted yields for DSR were slightly higher than under PTR, and yield declined gradually but similarly for both establishment systems as irrigation threshold increased. As in the field experiments, there was a large reduction in irrigation input through changing from CF to AWD, primarily due to less deep drainage, and a small reduction in ET. Additional irrigation at panicle initiation and flowering reduced the yield penalty under AWD but did not eliminate it completely.

Both the field and modelling studies suggest that DSR can be grown with comparable yield to PTR, and with lower irrigation input, provided that AWD water management with a low irrigation threshold (10-20 kPa) is used.

DECLARATION

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution to Sudhir Yadav and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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- Sudhir-Yadav, Gurjeet Gill, S S Kukal, E.Humphreys, R Rangarajan, U S Walia (2010). Water balance in dry seeded and puddle transplanted rice in Punjab, India. In: Gilkes R J, Prakongkep N, editors. Proceedings of the 19th World Congress of Soil Science; Soil Solutions for a changing World; ISBN 978-0-646-53783-2; Published on DVD; http://www.iuss.org; Working Groups 3.5; Paddy soils and water scarcity; 2010, Aug 1-6. Brisbane, Australia: IUSS; 2010, 43-46.

- Sudhir-Yadav, E.Humphreys, Gurjeet Gill, S S Kukal, R Rangarajan, U S Walia (2010). Studies on establishment methods and irrigation schedules to improve water productivity of rice. Presented at 3rd Rice Congress at Hanoi, Vietnam from November 8-12, 2010.

ACKNOWLEDGEMENT

At the very outset, with folded hands, I bow my head to the 'Almighty' Lord, whose grace glory and blessing gave me the courage in odd critical times for the successful completion of this degree.

First of all I put on record my deepest gratitude to my esteemed principal supervisor Dr Gurjeet Gill for his competent guidance, meticulous suggestions, constructive criticism which had enabled me to complete my research and degree successfully. No appropriate words could be traced in the present lexicon to convey my sublime obeisance to my supervisor Dr Elizabeth Humphreys whose unfold support, persistent inspiration and emotional attachment always catalysed my efforts. Her vast and deep knowledge of the subject, sense of dedication and above all, her parental nature throughout the tenure of this research, will be a part of memory forever. Words are too less to express by heartiest feelings to my supervisor Dr. S.S.Kukal whose support and encouragement helped me to develop interest in the research field. I couldn't imagine completing my field experiments without his professional and personal support.

I feel privileged to express my gratitude to U.S.Walia for his support during field experimentation. Many thanks to Dr R. Rangarajan and his team to providing instruments and enriched my experiment methodology with 'Tritium tagging' technique. I acknowledge the support of Dr K.K.Vashist and Dr S.K.Jaltoa for landing instruments for my field experimentation. Invaluable help rendered by Sandeep Singh, Sarbjeet and Hardeep Kumar during field experimentation is duly acknowledged.

I am also thankful to my friends Vicky, Kishan and Naveen Gupta for their invaluable help during my field experimentation. I duly acknowledge Dhamija and Pandher family for their personal support throughout my stay in India during field experimentation.

I wish to express my profound thanks to International Rice Research Institute (IRRI), Philippines for a very productive collaboration during my research tenure. Especial thanks to Dr B.A.M Bouman for making arrangement to access ORYZA model and for his constant support and guidance during my research. Many thanks to Dr. A. Boling for her assistance in basic training of ORYZA. I couldn't imagine to complete crop modelling part of my research without the support provided by Dr Tao Li. He not only helps me to run the model but also enabling me to understand the complexity of the model. His prompt action to modify the model as per my need would always be appreciated.

I would like to acknowledge the financial support from Australian Centre for International Agriculture Research (ACIAR) in the form of John Allwright Fellowship. I would like to thank Niranjala Seimon and Sharon Harvey for academic help. I also would like to acknowledge the financial, academic and technical support of University of Adelaide and its staff.

I would also like to acknowledge all my friends in Adelaide (Raj Setia, M.S.Mavi, Prem-Suman, Shankar, Paras, Hasim) for their personal and professional support during my PhD tenure.

Finally and most sincerely, I wish to deeply thanks to my family who through their blessing, support and love gave me strength to continue my work. I fumble for words to thank my better half Seema for her love, emotional support and persistent inspiration for my work.

All may not be mentioned but none is forgotten.

ACRONYMS

ANOVA	Analysis of variance
AWD	Alternate wetting and drying
CF	Continuous flooding
DAS	Days after sowing
DAT	Days after transplanting
DOY	Days of year
DSR	Dry seeded rice
EM	Establishment method
ET	Evapotranspiration
FL	Flowering
FSE	FORTRAN simulation environment
GHG	Greenhouse gases
GY	Grain yield
I	irrigation
IGP	Indo-Gangetic Plains
IS	Irrigation schedule
LAI	Leaf area index
LSD	least significant difference
P	Percolation
PAU	Punjab Agricultural University
PI	Panicle initiation
PTR	Puddled transplanted rice
R	Rainfall
S	Seepage
SAHEL	Soils in semi-Arid Habitats that Easily Leach
SARP	Simulation and Systems Analysis for Rice Production
SAWAH	Simulation Algorithm for Water flow in Aquic Habitats

SRI	System of rice intensification
STTIME	Start time
SWC	Soil water content
SWT	Soil water tension
WP_{ET}	Evapotranspiration based water productivity
WP_{I}	Irrigation water productivity
WP_{I+R}	Input water productivity

CHAPTER 1

REVIEW OF LITERATURE

1. Introduction

Rice and wheat are the world's two most important cereal crops, contributing 45% of the digestible energy and 30% of total protein in the human diet, as well as a substantial contribution to feeding livestock (Evans, 1993). In South Asia, rice and wheat are grown in rotation on large areas, and here the rice-wheat system is fundamental to the food security and livelihoods of hundreds of millions of rural and urban people (Timsina and Connor, 2001). In India, rice-wheat systems contribute more than 75% of total grain production (Dhillon et al., 2010).

1.1 The rice-wheat production system in the IGP

The Indo-Gangetic Plain (IGP) is composed of the Indus Plain (covering a large part of Pakistan, and much of Punjab and Haryana in India) and the Gangetic Plain (Uttar Pradesh, Bihar, and West Bengal in India, Nepal and Bangladesh) (Fig. 1). There are 12.3 Mha of agricultural land under rice-wheat systems in India, 2.2 Mha in Pakistan, 0.5 Mha in Nepal and 0.8 Mha in Bangladesh and about 85% of the total rice-wheat area in South Asia is located in the IGP (Ladha et al., 2000; Timsina and Connor, 2001). The area under rice-wheat systems in India increased substantially from 4 Mha to 12.3 Mha during the last 40 years (Hobbs and Morris, 1996; Timsina and Connor, 2001). During this period, both Haryana and Punjab became rice growing areas despite their semi-arid climate and relatively coarse textured soils. These two small states now contribute about 69% of the total food procurement by the Government of India (about 54% of the rice and 84% of the wheat) (Yadvinder-Singh et al., 2003). This large increase in production of rice and wheat, known as the "Green Revolution", was the result of both expansion of the cultivated area and increase in crop yields due to the introduction of improved varieties, higher input use, better agronomic practices, and expansion of irrigation by groundwater pumping. The rapidly increasing dependence on groundwater in this region is the result of the inability of the supply-driven canal system to meet the needs of the greatly increased areas under rice and wheat, the higher water requirement of new higher yielding wheat varieties, and strong support by policy makers (Raina and Sangar, 2004). More than 90% of the rice-wheat area in north-west India (Punjab, Haryana, and western Uttar Pradesh) is now irrigated using groundwater (Ambast et al., 2006).

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This figure is included on page 2 of the print copy of the thesis held in the University of Adelaide Library.

Fig. 1. Location of the rice-wheat area in the Indo-Gangetic Plain. Adapted from Hobbs and Gupta (2002).

In most of the IGP, rice is established by transplanting nursery seedlings (Pandey and Velasco, 1999). Before transplanting, puddling (churning of soil under saturated conditions) is performed in the main field as it helps in reducing water loss by percolation, destroys weeds and buries weed seeds, and makes the soil soft for transplanting (Adachi, 1992; Singh et al., 1995). The fields are normally kept flooded until shortly before harvest. Flooding also helps control weeds, and increases availability of nitrogen and phosphorus (Ponnamperuma, 1972). In contrast, wheat is grown in well-drained soil under good tilth and the crop is irrigated intermittently 2-6 times throughout the growing season. There are concerns that the edaphic conditions created for rice production could have a negative effect on the productivity of wheat which prefers more aerobic conditions.

1.2 Threats to the sustainability of the rice-wheat production system

Despite the success of the Green Revolution, there are grave concerns about the sustainability of the rice-wheat system. Over the past decade or so, yields of rice and/or wheat have declined or stagnated across the IGP, and factor productivity has declined (Ladha et al., 2003a; Ladha et al., 2007). National food grain production did not register any consistent increase from 1996-97 to 2006-07 (Fig. 2).

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Fig.2 National food production of India. Adapted from Dhillon et al. (2010).

The population of India is predicted to increase from 1.12 billion in 2008 to 1.35 billion by 2025 (UNESCO, 1995). Therefore, agricultural production needs to be increased, and the greatest pressure is on rice as it is the staple food for the majority of the population in India. Between 1995 and 2025, cereal production needs to be increased by about 25% on the same or less land, but the fact is that the rate of yield increase of rice and wheat in north-west India is declining, and in some situations yields are declining or stagnating (Ladha et al., 2003b; Ambast et al., 2006) (Fig. 3).

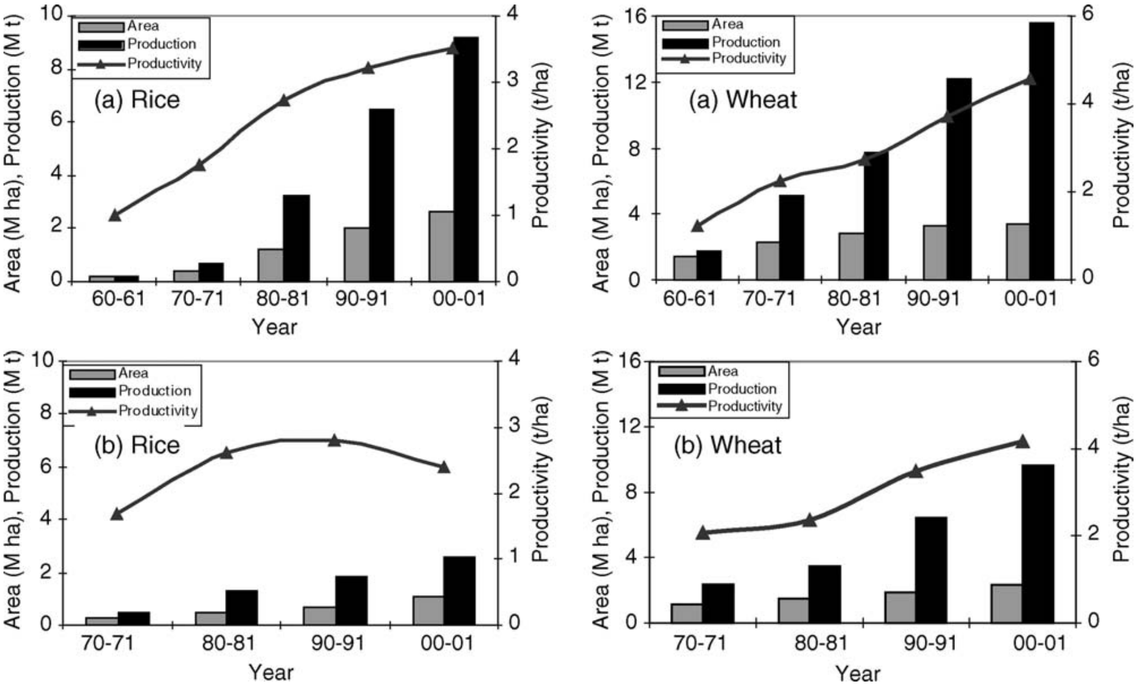

Fig 3. Area, production and productivity of rice and wheat in (a) Punjab and (b) Haryana. Adapted from Ambast et al. (2006).

One of the reasons for the decline in factor productivity could be related to the contrasting edaphic requirements for rice and wheat. For rice, the soil is puddled and traditionally kept under continuous submergence. In contrast, wheat grows best in well-drained soil having good soil structure. Over the past couple of decades, the conventional practice of growing rice has come under increasing criticism and researchers have started to explore alternative methods of rice production. The main drivers of the search for alternative methods of rice production are discussed in the following five sections.

1.2.1. Labour availability and cost

While agriculture has become highly mechanised in north-west India, virtually all rice is still transplanted manually over a period of a few weeks, requiring a huge labour force. Considerable hired labour is also involved in many other operations related to transplanted rice including uprooting nursery seedlings, weeding, application of herbicides and pesticides, irrigation and activities associated with the harvested grain (harvesting is mostly by large combine harvesters).

Fig.4 Trends in labour availability and cost. Adapted from Saharawat and Gathala (2011).

The agriculture sector in north-west India is highly dependent on migrant labour. In the past, millions of people from poor states in north-east India (Uttar Pradesh and Bihar) came to Punjab and Haryana to work in the agriculture sector. However, since the implementation of the National Rural Employment Guarantee Act in 2007, the flow of labour has decreased considerably because the Act promises 100 d paid work in people's home villages. Rapid economic growth in India has also increased the need for labour in non-agricultural sectors, which in turn has reduced labour availability for agriculture (Dawe, 2005; Saharawat and Gathala, 2011) (Fig. 4). Furthermore, the demand for labour in the agriculture sector tends to be very variable across the year, which may have led to labour movement to rapidly expanding non-agricultural sectors where the labour demand tends to be steady all year round.

Delay in transplanting beyond the optimum date due to labour scarcity is causing a reduction in rice yield in the north-west IGP. In Punjab, Mahajan et al. (2009) observed a yield decline of 7-16% when transplanting was delayed from 15 June to 5th July. A similar trend was also observed by Iqbal et al. (2008) in Pakistan. Previously, farmers could partially address labour scarcity through an earlier start to the rice planting program. However, this is no longer an option as transplanting before 10 and 15 June has been banned by the governments in Punjab and Haryana, respectively, which is causing a delay in transplanting to beyond the optimum time. Reduced labour availability is also pushing up the cost of transplanting, which in turn is squeezing the profit margin for farmers. In the recent past, the cost of hand-transplanting rice was around Rs 300/acre, but it went up to as much as Rs 2000/acre in 2009 (personal communication with farmers). Farmers in the north-west IGP are seeking alternatives to the hand-transplanting method of rice production. Mechanisation of rice establishment is now widely seen as an important area of research and development in the IGP.

1.2.2 Groundwater depletion

In north-west India, the primary sources of irrigation water are groundwater and river water distributed via canals. In the rice growing areas, groundwater is the predominant source of irrigation (Tyagi et al., 2005). In the second half of the 20th century there was rapid expansion in groundwater pumping from tubewells due to the inability of the supply-driven canal system to meet the needs of farmers (Raina and Sangar, 2004). For example, the number of tubewells in Punjab state increased from 98,000 in 1960-61 to about 1.2 million in 2009, even though the total geographical area of the state is only 5 Mha (Hira, 2009). As a result of assured water supply, between 1970-71 and 2001-02 the area under rice increased from 0.39 to 2.48 Mha in Punjab (Takshi and Chopra, 2004) and from 0.3 to

0.9 Mha in Haryana (Ambast et al., 2006). Unfortunately, the rapid increase in groundwater extraction and cropping intensity resulted in a steady decline in the depth to the groundwater in north-west India (Hira et al., 2002; Hira et al., 2004; Ambast et al., 2006; Hira, 2009; Rodell et al., 2009). The decline in the water table has accelerated alarmingly in some areas in the recent years; for example, in parts of Ludhiana district in central Punjab, the rate of groundwater decline increased from about 0.2 m year^{-1} during 1973 to 2001 to about 1 m year^{-1} during 2000 to 2006 (Fig. 5). Therefore farmers and governments are very concerned about future water scarcity.

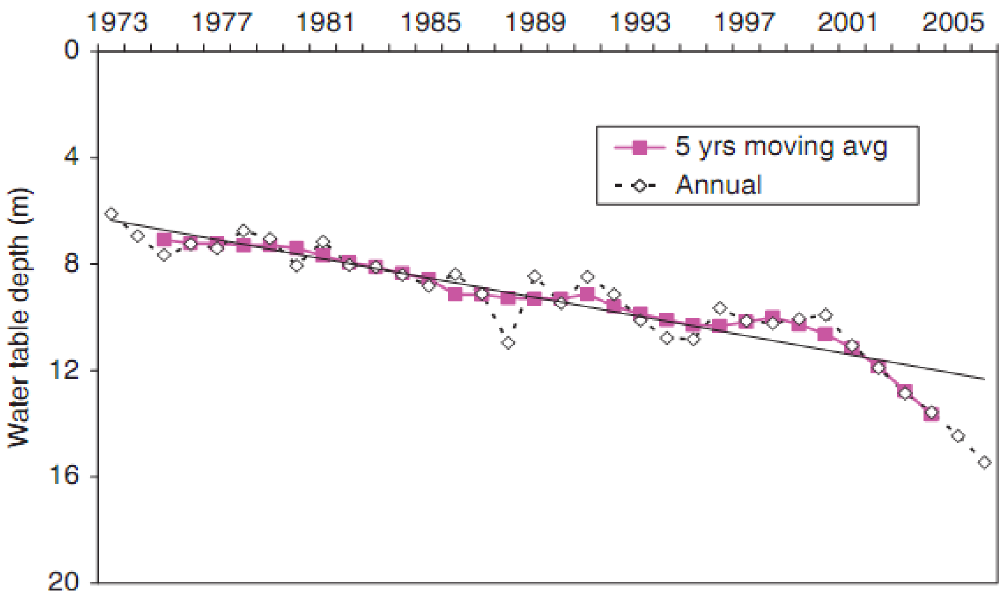

Fig.5 Depth of water table in the month of June, in Ludhiana district, Punjab India. Adapted from Humphreys et al. (2010).

1.2.3. Energy requirement for groundwater pumping and tillage

In north-west India, more than 60% of the groundwater pumps are powered by electricity (Shah et al., 2003). Because of the voting strength of the huge number of farmers, the state electricity boards are always under pressure to supply electricity free or at highly subsidized rates to the farmers. In 2007, about 28% of the electricity consumed in Punjab was supplied to the farmers at subsidized rates resulting in an annual loss of US$400 million to the state (Hira, 2009). Secondly, the supply of electricity to agriculture is very erratic due to the high demand in other sectors (industry, urban etc.) and the big gap in demand and supply. Therefore, many farmers need to supplement electricity with diesel-fuelled generators to power groundwater pumps. However, the price of diesel has increased rapidly during the last two decades, from just 23 US cents/litre in 1991 (Metschies, 2005) to the current rate of ~85US cents/litre (in September, 2010). For farmers, the decline in the groundwater table results in extra costs due to deepening of tubewells, replacement of centrifugal pumps with more expensive submersible pumps, and increased diesel consumption (when using generators). All these factors have increased the cost of production as well as increasing the likelihood of serious water scarcity in the future.

The conventional practice of rice production also consumes a lot of energy (in the form of diesel) for intensive tillage used to prepare the field before transplanting. Saharawat et al. (2010) reported that the conventional practice can require up to 14.2 h ha^{-1} of tractor time to prepare a field for rice production, which is a significant production cost.

1.2.4. Adverse effect of puddling on wheat yield

Puddling destroys soil aggregates, alters particle orientation, breaks capillary pores and results in massively structured topsoil and a dense hard pan of low permeability at a shallow (e.g. 15-25 cm) depth (Sharma and De Datta, 1986; Balloli et al., 2000; Kukal and Aggarwal, 2003a). Intense ploughing for puddling prior to rice transplanting has also been shown to reduce the soil organic carbon pool (Lal et al., 2004). The hardpan formed by puddling impedes the root growth of wheat (Boparai et al., 1992; Kukal and Aggarwal, 2003b) and reduces drainage, which can lead to temporary water logging.

In their review, Kumar et al. (2008) reported many studies where yield reduction of wheat ranged from 7 to 15% (0.2%) due to puddling for rice compared to non-puddled conditions (Fig. 6). However, not all studies reported a reduction in wheat yield as a result of puddling (Humphreys et al., 1995, 2005 ; Sharma et al., 2004).

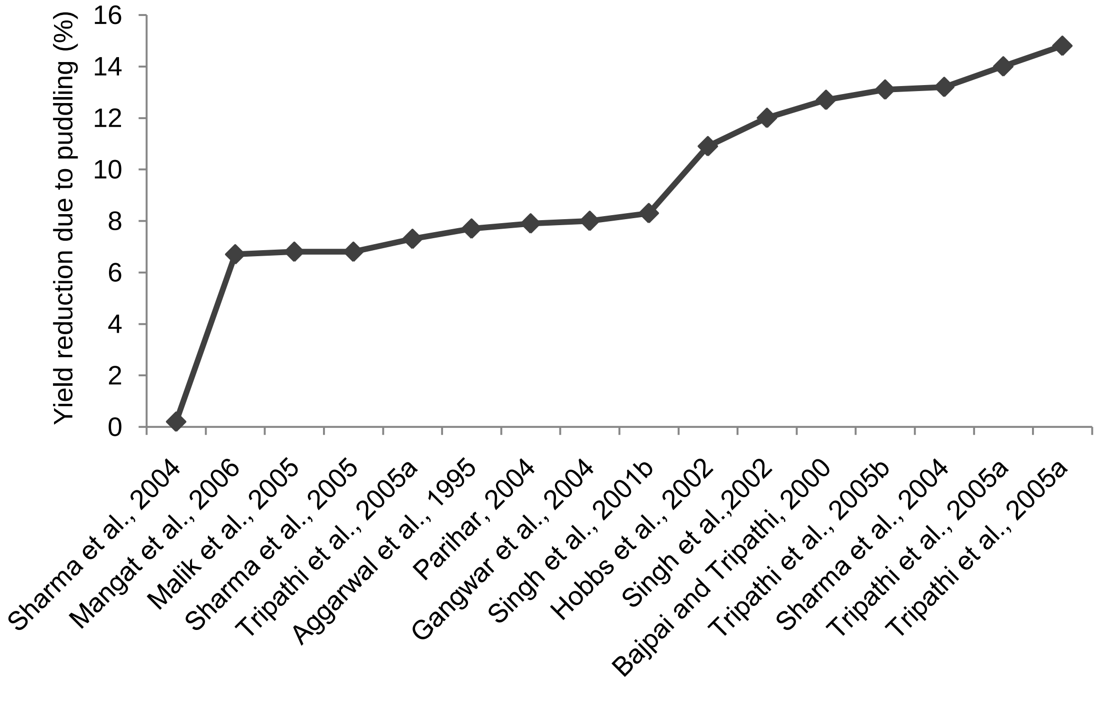

Fig.6 Effect of puddling of soil in rice on wheat yield. (adapted from Kumar et al., 2008)

Puddling results in a hard, massively structure topsoil which requires many tillage passes to create a friable seedbed. This process requires considerable energy (Malik et al., 2004) and delays wheat planting, which leads to a yield reduction of 1–1.5% per day for every day that sowing is delayed beyond the optimum date (early November) (Ortiz-Monasterio et al., 1994). Pathak et al. (2003) reported a yield loss of 35-60 kg $d^{-1}ha^{-1}$ in the IGP because of delay in wheat planting. Therefore, in addition to improving soil structure for wheat growth, avoidance of puddling can help reduce the turn around time between rice harvest and wheat sowing for the many farmers who still use conventional tillage for wheat.

1.2.5. Environmental issues

The conventional practice of rice production keeps the soil flooded and therefore anaerobic almost throughout the rice season. Wetland rice systems emit large quantities of methane (CH_4), and account for 8.7–28% of total anthropogenic emissions (Mosier et al., 1998).

Methane is one of the major greenhouse gases (GHG) contributing to global warming. The annual methane emissions from rice fields are 3%–10% of global emissions of about 600 Tg (Kirk, 2004). Estimates of annual methane emissions from the principal rice producers, China and India, are in the range of 10–30 Tg (Bouman et al, 2007a). Emission of methane from rice fields is very sensitive to management practices (including water management), so improved management of rice to reduce GHG emissions is an important target (Wassmann et al., 2004).

2. Potential solutions for improving the sustainability of rice-wheat cropping systems

Replacement of the puddled transplanted rice production system with a non-puddled, direct seeded system is a potential solution to many of the above problems including labour scarcity, the high costs of puddling and manual transplanting, and the adverse effects of puddling on soil properties for wheat. Changing water management from continuous flooding (CF) to alternate wetting and drying (AWD) also has the potential to greatly reduce irrigation input (and thus the cost of irrigation and consumption of fuel) and methane emissions from rice fields, however, whether it will help reduce groundwater depletion is less clear.

2.1. Alternative rice establishment technology

There are several technologies for rice establishment which have the potential to reduce one or more of the threats to the sustainability of rice-wheat systems (section 1.2). These technologies include mechanical transplanting, raised beds, dry seeding and wet seeding. All technologies have their advantanges and disadvantages. . For example, mechanical transplanting reduces labor requirement, and can be done in non-puddled soil, reducing tillage costs, diesel consumption and soil degradation. But mechanical transplanting is complex technology which requires the use of expensive machinery for a single function, and carefully raised seedlings. However, if implemented well, mechanical transplanting has the advantage of being able to flood the crop for a couple of weeks after transplanting, an extremely beneficial practice for weed control. Similarly, permanent raised beds can be established by zero till dry seeding, however, many studies in the NW IGP have shown a decline in grain yield over time (Sharma et al., 2002; Khan et al., 2003; Jat et al., 2008; Kukal et al., 2008), and in some studies increased irrigation amount (Humphreys et al., 2008). Dry seeded rice on the flat does not require specialized farm implements, and it can be sown using the same seed drill in more or less the same manner as other crops such as wheat, with or without prior cultivation. Furthermore, the development of the technology is relatively advanced and in early stages of adoption. However, there are still aspects of the technology requiring further research. In view of the many potential benefits of DSR, and the potential for relatively rapid adoption, this review considers the pros and cons of replacing PTR with DSR, and the knowledge gaps in relation to water management.

2.1.1 Dry seeded rice

2.1.1.1 Introduction

Like other cereal crops, rice can be sown directly into the main field instead of first raising the seedlings in a nursery and later transplanting them in the main field. Direct seeded rice can be either wet seeded or dry seeded. In wet seeding, the land is puddled as for PTR and the seed is broadcast or placed on the surface in rows with a drum seeder. In dry seeding, dry or primed seed is broadcast or drilled in a tilled soil, or sown with a zero till drill in a similar way to wheat. Wet seeding is more popular in the wetter climates of Thailand, Malaysia, Vietnam and Philippines (Sattar, 1992; Pandey and Velasco, 1999), whereas most of the research and early adoption of direct seeded rice in the IGP has been for dry seeding. Therefore this thesis deals with dry seeded rice which is abbreviated as “DSR” from here on. Further, it should be noted that DSR refers only to an establishment method, and water or other management practices need to be specified separately. For example, water management in both PTR and DSR can vary from continuous flooding for all or most of the duration of the crop, to frequent or infrequent alternate wetting and drying.

2.1.1.2. Advantages of DSR over PTR

According to Pandey and Velasco (2005), low wages and adequate availability of water favour transplanting, whereas, high wages and low water availability favour DSR (Fig. 7). Direct seeding for rice establishment can save labour by up to 50%, reduce low plant density risk and save water (Pandey and Velasco, 1999). Saharawat et al (2010) reported human labour utilisation over the whole cropping season of 56 d ha^{-1} for DSR, 13% lower than for PTR. A study conducted at Ludhiana (Punjab) found a net labour cost saving of Rs 1250/ha with DSR (Gill and Dhingra, 2002).

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Fig.7 Wage rate and water availability as determinants of preferred crop establishment methods. Adapted from (Pandey and Velasco, 2005).

In the central to eastern Ganges Plains, where rice establishment is often reliant on the start of the monsoon, dry seeding can provide an opportunity for timely establishment on the first rains (usually 1- 2 supplementary irrigations are needed after sowing) prior to the onset of the monsoon, rather than waiting for sufficient rain to be able to puddle and flood the soil for transplanted rice. Dry seeding of rice offers a good opportunity for conserving irrigation water (Dawe, 2005; Humphreys et al., 2005) by using pre-monsoon rainfall more efficiently for crop establishment and the early stage of crop growth (Tuong, 1999). DSR has also proved to be an important technique to reduce methane emission. In a field experiment in the Philippines, DSR with AWD reduced CH_4 emissions by 18% compared with transplanting (Corton et al., 2000). Wassmann et al. (2004) suggested that CH_4 mitigation can be enhanced by up to 50% if DSR is combined with mid-season drainage. However, the net effect of DSR on GHG emissions also depends on N_2O emissions which increase under aerobic conditions.

Some studies have shown that dry seeded rice matures 10-15 days earlier than PTR and therefore vacates the rice field earlier thus favouring more timely planting of wheat (Giri, 1998; Singh et al., 2006; Singh et al., 2009a). However, other researchers (Cabangon et al., 2002; Kato et al., 2009) reported delayed maturity (3-29 d) of DSR compared with PTR.

2.1.1.3. General yield trend of DSR

In countries like India, Pakistan, Nepal and Bangladesh, population pressure and food demand mean that land productivity (yield) is a prime consideration in determining whether alternative crop production technologies will be adopted. To date, most research has indicated an average yield penalty of around 10% with DSR compared with PTR, but losses can be as much as 33% (Table 1). The higher yield penalties in DSR were primarily due to high weed infestation (Yadav et al., 2008), micro-nutrient deficiency (Choudhury et al., 2007; Kreye et al., 2009) and nematode infestation (Singh et al., 2002; Choudhury et al., 2007).

At Karnal, Haryana, Goel and Verma (2000) observed similar yield of PTR (5.5 t ha^{-1}) and DSR in the first two years of experimentation, but yield decreased by 15 and 9% in the third and fourth years, respectively, due to severe weed infestation. Hobbs et al. (2002) observed a non-significant decrease of 5 and 8% grain yield of DSR on sandy loam and silty loam soils, respectively, and argued that the dense canopy of DSR provided favourable conditions for multiplication of leafhoppers. Bhushan et al. (2007) and Saharawat et al. (2010) found spikelet sterility as one of the causes of yield penalty in DSR.

Table 1. Grain yield response of DSR relative to PTR in different soils at different locations in the IGP

Soil type	Grain yield of PTR (t ha^{-1})	Yield response of DSR (% change)	Location	Reference
Silty loam	4.2	-33.3	Faizabad, India	Yadav et al. (2008)
Sandy loam	5.5	-23.6	New Delhi, India	Choudhury et al. (2007)
Loam	5.4	-22.2	New Delhi, India	Choudhury et al. (2007)
Silty clay loam	5.7	-9.3	Pantnagar, India	Singh et al. (2004)
Silty clay loam	5.7	-8.6	Pantnagar, India	Tripathi et al. (2005a)
Silty loam	6.1	-8.2	Pantnagar, India	Hobbs et al. (2002)
Clay loam	7.2	-8.1	Kaithal, India	Saharawat et al. (2010)
Silty clay loam	5.4	-7.0	Pantnagar, India	Sharma et al. (2005)
Silty clay loam	6.9	-5.8	Pantnagar, India	Singh et al. (2008)
Sandy loam	5.6	-5.4	Pantnagar, India	Hobbs et al. (2002)
-	5.5	-5.0	Karnal, India	Goel and Verma (2000)
Silty loam	7.3	-4.1	Modipurum, India	Bhushan et al. (2007)
Sandy loam to loam	4.9	-4.1	Meerut, Ghaziabad and Bhulandshar, India	Saharawat et al. (2009)
Sandy loam to clay loam	6.3	-1.6	Karnal, India	Saharawat et al. (2009)
Silty clay loam	5.3	+1.9	Bhairahawa, Nepal	Hobbs et al. (2002)
Sandy loam	6.6	+3.8	Ludhiana, India	Gill (2008)
24 villages	3.9	+12.4	Ballia, India	Singh et al. (2009a)

In contrast to the results of the above replicated experiments, farmer participatory research trials in 24 villages at Ballia, Uttar Pradesh showed an average increase of 13.7% grain yield with DSR as compared to PTR (3.87 t ha^{-1}) (Singh et al., 2009a). They argued that the high rainfall and fine textured soils in eastern IGP enabled DSR to perform similarly or better than PTR, whose yield levels were quite low. In sandy loam soils at Ludhiana (India), the grain yield of DSR was similar to that of PTR (6.6 t ha^{-1}) (Budhar et al., 1990; Gill, 2008). Similar observations have been also recorded by Gangwar et al. (2008), and

Hobbs et al. (2002) also reported a slight edge of 2% high yield with DSR on silty clay loam soils in Nepal.

Thus there is considerable variation in the performance of DSR relative to that of PTR between different studies. The reasons for variation in DSR performance probably include sub-optimal management of a range of factors such as weeds, macro- and micro-nutrients, soil borne pathogens and water management. Some authors (Bhushan et al., 2007; Saharawat et al., 2010) suggested water deficit stress as a cause of high spikelet sterility in DSR. Furthermore, water management and soil water status influence weed incidence and the efficacy of herbicides, the availability of macro- and micro-nutrients, and the activity of soil-borne pathogens such as cereal cyst nematode. Therefore, determining the optimum water management for DSR to avoid yield loss, while minimising input, is an important priority.

2.2. Alternative irrigation management practices

The need to conserve irrigation water is one of the major drivers of change from the traditional practice of PTR with prolonged periods of flooding, or continuous flooding, to DSR with AWD water management. Water management techniques can play a pivotal role not only in reducing irrigation input (and groundwater depletion in some situations) but also other adverse environmental impacts. For example, AWD reduced CH_4 emissions by 30–50% but with 16% yield penalty at 10 kPa at 5 cm soil depth in China (Lu et al., 2000). Pathak et al. (2005) evaluated the GHG emissions from Indian rice fields and observed that intermittent flooding reduced the emissions of CH_4 and CO_2 but increased N_2O emission. However, the total global warming potential (GWP) of rice producing areas in India decreased from 131-273 Tg CO_2 equivalents/yr with CF to 92–212 Tg CO_2 equivalents/yr with AWD.

Reduction of hydrostatic pressure has been suggested as one of the approaches for reducing field water losses in the forms of seepage (S) and percolation (P) (drainage below the root zone) (Bouman et al., 1994; Kukal and Aggarwal, 2002). Seepage plus percolation (S+P) can be as high as 25 mm d^{-1} during land preparation for rice establishment, because soil cracks do not immediately close completely after irrigation (Tuong et al., 1996). Typical S + P rates for paddy fields during the crop growth period vary from 1-5 mm d^{-1} in heavy clay soils to 25-30 mm d^{-1} in sandy and sandy loam soils (Wickham and Singh, 1978; Jha et al., 1981). Based on the understanding of various components of the water balance, researchers are developing water saving technologies to reduce hydrostatic pressure such as continuous soil saturation (Borrell et al., 1997; Tabbal et al., 2002) and AWD (Wu, 1999; Bouman and Tuong, 2001; Li, 2001).

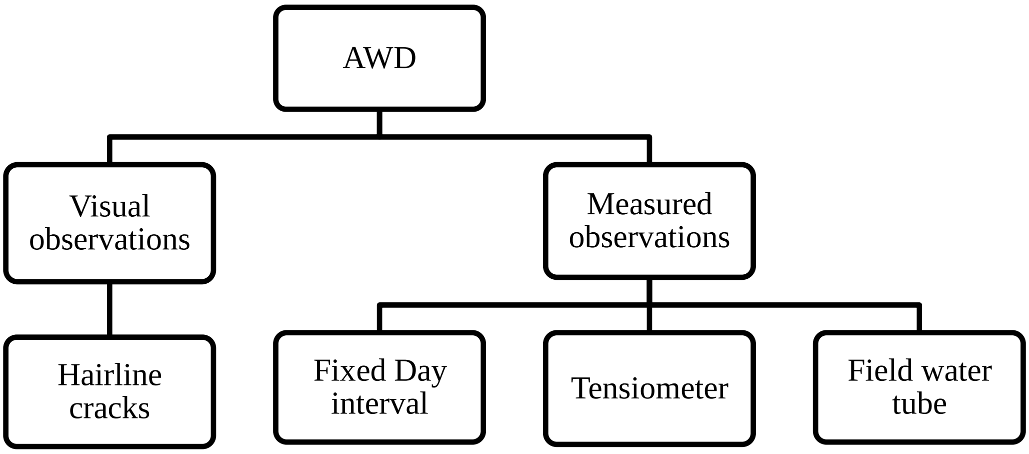

Fig 8. Different approaches for irrigation scheduling of AWD in rice.

AWD can be managed based on visual or measured observations (Fig. 8). Visual observations include irrigation scheduling when hairline cracks start to appear on the soil surface (Vijayakumar et al., 2006; Bhushan et al., 2007; Singh et al., 2009a; Saharawat et al., 2010). The simplest way of implementing AWD based on measured observations is the one where irrigation is applied at a set number of days after ponding ceases (Belder et al., 2004; Arora et al., 2006). Another observation based method of AWD is based on a set value of soil water tension (Hira et al., 2002; Kukal et al., 2005) measured by tensiometer.

The main principle behind all these technologies is to reduce the hydraulic head and the period during which the soil is saturated, reducing percolation and seepage and thereby irrigation requirement. However, while hair line cracks and day interval approaches are broad indicators of soil drying, they do not provide a good indication of soil moisture status in the root zone. The tendency of a soil to crack depends on the nature and amount of clay, tillage history, and the rate of soil drying, and the latter depends on evaporative demand and the size of the crop canopy and growth stage. Therefore, it is very important to consider all these factors while scheduling irrigation. Scheduling irrigations using tensiometers accounts for such variables as soil tension is a direct measure of soil water availability to the plants at the depth of measurement. For a given soil, the soil tension at any depth below the soil surface is related to the depth to the perched water table (Soylu et al., 2011). Field water tubes, also called '*Panipipes*', are simple pipes (e.g. PVC, bamboo) which allow the farmer to see the depth to the perched watertable. The pipes are typically 30 cm long with an inner diameter of 10 cm, inserted into the soil to a depth of 15-20 cm, and the soil is removed from inside the tube. The section of the panpipe below the soil surface is perforated to allow water to enter the pipe. The farmer can assess the water level in the soil by simply looking for the presence of the watertable, or measuring the depth of water in the pipe.

2.2.1. AWD in PTR

2.2.1.1. Crop performance under AWD

It is important to avoid yield loss in shifting from CF to AWD, but it is well established that rice is very sensitive to water deficit stress as the soil dries below saturation, with a critical threshold at around 10 kPa soil water tension (SWT) (Bouman and Tuong 2001). Therefore it is important to understand how to manage AWD to avoid yield loss. Many studies have shown that AWD can be managed to maintain grain yield in rice (Choudhury et al., 1991; De Dios et al., 2000), and that it sometimes even leads to an increase in yield

(Wu, 1999; Mao et al., 2000; Yang et al., 2007). Yield benefits from AWD have been ascribed to better root vigour and depth (Mao et al., 2000); reduced lodging, pests, and diseases (Yi, 1999); better soil oxygenation (Wang, 1999), reduced lodging in wet seeded rice in Vietnam (T.P. Tuong, pers. comm.), and increased tillering and panicle density in Bangladesh (E. Humphreys, pers. comm.). Cheng (1983) reported that aerobic soil conditions favoured the removal of toxic chemicals from the rhizosphere.

On sandy loam soils in Punjab, Hira et al. (2002) and Kukal et al. (2005) observed similar yields of PTR with AWD irrigated on the basis of soil water tension (SWT) (thresholds of up to 24 kPa at 15-20 cm soil depth) and with CF. On a similar soil in Jiangsu (China), Zhang et al. (2008) observed significantly higher grain yield when irrigation was scheduled at 25 kPa at 15-20 cm soil depth compared to CF. Higher yield under AWD was associated with more filled grains per panicle and higher average grain weight than in CF. But grain yield decreased when the soil water tension threshold increased from 25 to 50 kPa. In another experiment, Zhang et al. (2009) reported 10% higher grain yield when irrigation was applied at 15 kPa at 15-20 cm soil depth than CF (814 g m^{-2}) with irrigation water saving of 28%. They argued that the higher yield in AWD was primarily due to higher root oxidation activity, cytokinin concentration in roots and shoots, leaf photosynthetic rate, and activities of key enzymes involved in sucrose-to-starch conversion in grains. However, there was a yield decline when the SWT threshold increased from 15 to 30 kPa.

In contrast, other studies have shown a yield decline with AWD (Borell et al., 1997, Lu et al., 2000, Bouman and Tuong 2001). On a sandy loam soil in Punjab, India, Singh et al. (2009b) observed similar yield (average of 3 years data) when irrigation was applied at 2d interval as compared to CF (5.7 t ha^{-1}), however, there was significant yield penalty of 7% in loam soil. Under a similar environment, Arora et al. (2006) observed a significant yield decline of 7 % with AWD (2-d interval) compared with CF (8.6 t ha^{-1}). Similarly, Cabangon et al. (2003) reported a significant yield decline with AWD when soil water potential at 10 cm depth dropped below -20 kPa. However, in all studies where AWD resulted in a yield decline, the irrigation water productivity was higher with AWD than CF because the reduction in irrigation input was larger than the loss of yield.

The reasons for the contrasting effects of AWD on yield in different studies are not known, but could be related to the incidence of water deficit stress at critical growth stages known to be sensitive to water deficit. It is well-established that water stress between panicle initiation (PI) and flowering causes floret sterility and thus reduces the number of grains per panicle and yield (O'Toole and Moya, 1981; Garrity and O'Toole, 1994; Boonjung and Fukai, 1996; Bouman and Tuong, 2001). Therefore, there is a need to identify irrigation thresholds which minimize irrigation input while maintaining yield. Recently, guidelines for ‘safe AWD’ have been developed which aim to ensure that yield is maintained (Bouman et al., 2008). Safe AWD includes short periods of ponding at critical developmental stages of the crop (for 2 weeks after transplanting, and from heading to anthesis), and irrigating whenever the perched water table falls to 15-20 cm below the soil surface throughout the rest of the growth period.

2.2.1.2. Irrigation water savings and water productivity under AWD

In north-west India, many researchers have observed large irrigation water savings (10–64%) with AWD in PTR in comparison with CF, and with no or only small effects on yield (Table 2). In AWD, the introduction of periods of non-submerged conditions of several days during the growing season results in reduced water input and increased water productivity, unless the soil is allowed to dry to the degree that cracks are formed through the plough sole (Bouman and Tuong, 2001). Alternate wetting and drying has been shown to reduce seepage and deep drainage losses, particularly on more permeable soils (Tuong et al., 1994).

In Pantnagar, Mishra et al. (1990) observed an irrigation water saving of 23-44% under shallow (0.9 m) and medium (1.3 m) water table conditions when irrigation was applied 1 d after ponding had ceased, in comparison with CF. Irrigation water productivity (WP_I) was 26-73% higher with the 1-d treatment than CF. However, the WP_{ET} was similar in both the treatments. Similar observations have been also reported with a 2-d interval (Singh et al., 2001a; Arora, 2006; Singh et al., 2009b) in Punjab, India under deep watertable conditions.

Table 2. Yield and irrigation water saving response of PTR to AWD as compared to CF in IGP, India

AWD approach	Irrigation water saving (%)	Yield response (%)	Soil type	Location	Reference
1-d	23-44	-2 to -7	Clay loam	Pantnagar, Uttarakhand	Mishra et al. (1990)
3-d	34	+48	-	Pusa, Bihar	Batta et al. (1998)
3-d	34	+33	Loam to Sandy loam	Chiplimma, Orissa	Batta et al. (1998)
2-d	13-23	-2 to -8	Sandy loam	Ludhiana, Punjab	Singh et al. (2001a)
2-d	12-25	-2 to -6	Silty clay loam	Ludhiana, Punjab	Singh et al. (2001a)
16 kPa	25-30	0 to -5	Sandy loam	Ludhiana, Punjab	Kukal et al. (2005)
2-d	10-36	0 to -12	Sandy loam	Ludhiana, Punjab	Arora et al. (2006)
2-d	23-51	-15 to +10	Sandy loam	Ludhiana, Punjab	Singh et al. (2009b)
2-d	45-64	-14 to +6	Loam	Phillaur, Punjab	Singh et al. (2009b)

In Korea, Won et al (2005) observed irrigation water savings of 33% and 46% higher irrigation water productivity with shallow intermittent irrigation (2 cm) compared to typical deep water irrigation (10 cm). The irrigation water was applied after the disappearance of flooded water and the field was dried at the maximum tillering stage for 10 days. As the amount of water applied decreased, root density in the shallow layer decreased but there was an increase in root density at depth.

While studying the system of rice intensification (SRI), Vijayakumar et al. (2006) in Coimbatore, India observed that the application of irrigation on appearance of hairline cracks produced similar yield as the conventional practice where water was applied 1 d after the disappearance of irrigation water. However, the total input water productivity was significantly higher in the treatments where water was applied on the appearance of hairline cracks from that in conventional practice.

The amount of irrigation water saving varies with depth of the groundwater table and soil texture. With a shallow water table (0.05-0.9m), Belder et al. (2004) observed a 15-18% irrigation water saving with AWD (10 kPa irrigation threshold) compared to CF in silty clay loam soils of China. However, this irrigation savings increased to 45-64% on a loam soil in Punjab (Singh et al., 2009b) where the groundwater table was very deep (22 m).

2.2.2. AWD in DSR

2.2.2.1 Crop performance

Two of the major aims in the development of DSR technology for north-west India are to achieve yields comparable to (or higher than) those of PTR with CF/safe AWD, while reducing irrigation input. However, only a few studies have compared DSR and PTR with AWD irrigations scheduled using the same criteria for both establishment methods.

On a silty loam soil in U.P., India, Bhushan et al. (2007) observed similar yields of conventional PTR and zero-till DSR when irrigation was scheduled at the appearance of hair line cracks (~33kPa at soil surface) after maintaining saturation (daily irrigation) for the first 2 weeks after germination of the DSR or flooding for the first 2 weeks after transplanting. Among yield attributes, panicle density was higher in DSR than PTR, however, this was countered by higher floret sterility was in DSR. In the western IGP, India, Saharawat et al. (2009) also observed similar grain yields of DSR and PTR at Karnal (Haryana), but significantly lower yield of DSR at Modipuram (UP), with irrigation scheduled on the appearance of hairline cracks in DSR while PTR was flooded for the whole crop season.

In Japan, Kato et al. (2009) observed similar or significantly higher yield and irrigation water productivity of DSR with several aerobic rice cultivars when irrigation was scheduled at 60 kPa at 20 cm soil depth compared to PTR where 5-10 cm water depth was maintained continuously. In this study, the field was frequently irrigated by sprinkler which probably kept the upper root zone wetter than at 20 cm soil depth, and which may explain the fact that there was no yield decline at thresholds up to 60 kPa at 20 cm. In contrast, in a flood irrigated system, the upper root zone is likely to be drier and for longer periods than at 20 cm soil depth.

Based on a modelling study, Bouman et al. (2007b) concluded that there was no adverse effect of irrigation thresholds of up to 30 kPa under shallow groundwater (60 cm) conditions for dry seeded aerobic rice. However, under deeper groundwater conditions (190 cm), there was an 11% decline in yield when irrigation the threshold was ≥21 kPa. In another simulation study on different soil types in China, Xue et al. (2008) predicted only a small effect of increasing the irrigation threshold from 10 to 100 kPa on yield of dry seeded aerobic rice, however, there was a sharp decline in rice yield when the threshold soil water tension increased beyond 100 kPa.

Thus the few studies comparing DSR and PTR with the same water management, and those comparing DSR with AWD and PTR with CF, show variable results in terms of grain yield.

2.2.2.2 Water savings and water productivity

In most of the published studies, DSR with AWD has been compared with the conventional practice of PTR with CF. To date there has been very little published about water savings and water productivity with different AWD treatments within DSR, and how this compares with PTR with the same water management regimes.

On a silty loam soil in Uttar Pradesh, India, Bhushan et al. (2007) observed 19% irrigation water savings and 11% increase in input water productivity (WP_{I+R}) (0.20 g grains L^{-1})

with zero tilled DSR when irrigation was scheduled at 33 kPa compared to PTR with CF. On a sandy loam soil, Choudhury et al. (2007) observed an irrigation water saving of ~50% in DSR irrigated every second day in comparison with PTR with CF. Both irrigation and water input productivity were significantly higher in DSR than in PTR. However, there was no significant difference in WP_{ET}. They observed a similar trend on a loam soil except that WP_{ET} was significantly higher in DSR. In a two year field experiment in Haryana, Saharawat et al. (2009) observed 9-11% irrigation water saving with DSR irrigation when irrigated on the appearance of hairline cracks compared with continuously flooded PTR.

In a simulation study, Xue et al. (2008) observed a sharp decline in water input when the irrigation threshold increased from 10 to 50 kPa at 20 cm soil depth, however, they observed highest WP_{I+R} at an irrigation threshold of 100-200 kPa. The WP_{ET} in their study was almost constant and highest for irrigation thresholds between 10 and 100 kPa.

2.2.3. Nature of water savings with AWD

There are many studies which indicate irrigation water saving with AWD in both DSR and PTR. However, there is a wide variation in the percentage of water saving across these studies. The discrepancies among different researchers regarding water savings might be due to slight differences in the use of terminology related to water use. Some researchers define crop water use as evapotranspiration; however, others refer to crop water use as the total water input in crop production. Secondly, the objective of water saving could be different for different people. For farmers, it will be to reduce costs and/or to ensure that there is adequate water available for all their fields. For farmers for whom irrigation water is limiting, either due to limited physical availability or affordability, the objective will be to maximise WP_I. For a water resource manager, the objective will be to maximise WP with respect to water depletion from a higher spatial scale such as a sub-catchment or catchment. This normally means maximizing WP_{ET}. Although deep drainage is a loss from individual fields, this water will re-enter the groundwater and could be available for reuse elsewhere in the catchment. Similarly, runoff to adjacent fields or surface water systems can be re-used, and water stored in the soil profile can be used by the next crop. Therefore, reducing ET is necessary to produce real water savings at the catchment scale, unless drainage or runoff water flows into non-reusable sinks such as saline groundwater or the sea.

There are few field studies which have attempted to determine the nature of the water savings as a result of PTR-AWD or DSR-AWD in comparison with conventional PTR. Singh et al. (2002) reported that about 51% of total water applied was lost through deep percolation in PTR (CF with 5±2 cm water depth) while percolation loss was about 45% in DSR irrigated to maintain near-saturated conditions. The ET losses in DSR (556 mm) were 29% lower than in PTR but at a cost of 23% yield penalty. Choudhury et al. (2007) also observed significantly lower ET in DSR (29-37%) than PTR but again accompanied by yield loss.

In Malaysia, Cabangon et al. (2002) observed significantly higher seepage and percolation in PTR than in DSR during the whole crop season, and especially during the pre-establishment phase. Over the whole crop season, the total ET of PTR (1200 mm) was significantly ($P < 5\%$) higher than that of DSR (~1000mm).

There are some modelling studies which have attempted to determine the nature of the irrigation water saving with AWD in north-west India. Arora (2006) used the ORYZA2000 model to compare CF and AWD for PTR on a sandy loam for 12 years of weather data at Ludhiana, Punjab. The AWD treatment involved CF for 2 weeks after transplanting, and thereafter irrigation (50 or 75mm) 2 d after the disappearance of free water from the soil surface. Alternate wetting and drying reduced the average irrigation amount by about 25–30%, but ET was reduced by only about 30 mm. Under a similar environment, Singh et al (2001a) also predicted relatively small difference of up to 109 mm in ET compared to the effects on percolation of a range of puddling intensity and irrigation treatments. Based on 8 published studies, it can be observed that the predicted ET of rice in the north-west IGP varies between 408-840 mm (Table 3).

Table 3. Measured/predicted ET values of rice in north-west India

ET (mm)	Treatment Type	Methodology of ET estimation	Location	Reference
521-759	Irrigation schedule	Lysimeter	Pantnagar, India	Mishra et al. (1990)
408-517	Irrigation schedule and puddling intensity	Model prediction (SAWAH)	Punjab, India	Singh et al. (2001a)
553	Cropping system	Model prediction (local model)	Punjab, India	Jalota and Arora (2002)
551-734	Irrigation schedule, puddling intensity and transplanting time	Model predictions (ORYZA2000)	Punjab, India	Arora (2006)
457-840	Establishment method and irrigation schedule	Calculated as residual of water balance equation	New Delhi, India	Choudhury et al. (2007)
536-728	Transplanting time	Model prediction (CROPMAN)	Punjab, India	Chahal et al. (2007)
460-650	Establishment method	Model prediction (CERES)	Punjab, India	Humphreys et al. (2008)
610-750	Transplanting time, cultivar and irrigation schedule	Model prediction (CropSyst)	Punjab, India	Jalota et al. (2009)

The maximum difference in ET between different treatments within a study was predicted by Choudhury et al. (2007) who predicted a decline of 384 mm ET with raised beds irrigated at 20 kPa SWT at 20 cm soil depth on sandy loam and loam soils compared to PTR at CF. However, this decline was at the cost of huge yield penalty (44%)

3. Crop models to investigate components of the water balance and productivity of rice as affected by management and site conditions

3.1. The importance of crop models

While field experiments can be used to explore crop management options, the findings are season and site specific, and the number of options that can be evaluated is limited. Crop growth simulation models provide the capability of exploring the effects of management, weather and soil conditions on crop performance. By running scenarios using long term historical weather data, they enable analysis of the likelihood of different outcomes.

Accurate determination of the components of the water balance in a cropped field is essential to understand the fate of water and design crop management practices to achieve the most effective use of water. The water-balance components can be quantified through field experiments, but this is expensive and time consuming, and can only be done for a very limited number of case studies. Crop models can be used to estimate components of the water balance, and the nature of any irrigation water savings as a result of changed management. Before a crop model can be used, it needs to be calibrated and validated with independent experimental data of the local situation. Once validated, simulation studies can be used to evaluate a wide range of management practices including establishment method and irrigation scheduling, for a wide range of soil and seasonal conditions.

3.2. Rice crop models

Many rice growth models have been reported in the literature over the last 30 years including RICEMOD for potential production and rainfed environments (McMennamy and O'Toole, 1983), SIMRIW for potential production and effect of climate change (Horie et al., 1992), RLRice for rainfed rice (Fukai et al., 1995), two generic crop growth models WOFOST (Van Keulen and Wolf, 1986; Hijmans et al., 1994), and MACROS (Penning de Vries et al., 1989) for potential and water limited conditions.

The most frequently cited rice models in South Asian conditions are CERES Rice (Timsina and Humphreys, 2006) and ORYZA2000 (Bouman et al., 2001, 2007b). CERES Rice is one of many models contained in the DSSAT (Decision Support System for Agrotechnology Transfer) which provides a facility for simulating crop sequences (Jones et al., 2003). ORYZA2000 was incorporated into a different modelling framework (APSIM - Agricultural Production Systems Simulator) several years ago to also provide the capability of simulating rice-based cropping systems (Zhang et al., 2007; Gaydon et al., 2006). APSIM is a modelling framework that allows models of crops, pastures, soil water, nutrients and erosion to be flexibly configured to simulate diverse production systems (Keating et al., 2003). However, there have been several improvements to ORYZA2000 since then (Tao Li, pers. comm.), which have not yet been incorporated into APSIM-ORYZA.

3.3. ORYZA2000

Although ORYZA2000 is a single crop model, it was chosen for this study because it has recently been evaluated and used successfully for studies on irrigation management in dry seeded aerobic rice in China (Feng et al., 2007; Bouman et al., 2007b; Xue et al., 2008), because it is freely available, and because of the opportunity to collaborate with the model developers and to improve the model as needed. CERES Rice has not been updated for many years, and the capacity for backup support from the model developers is very limited.

The ORYZA2000 model is the successor to a series of rice growth models developed in the 1990s in the project "Simulation and Systems Analysis for Rice Production (SARP)" (ten Berge and Kropff 1995). It is an update and integration of the models ORYZA1 for potential production (Kropff et al., 1994), ORYZA_W for water-limited production (Wopereis et al., 1996), and ORYZA-N for nitrogen-limited production (Drenth et al., 1994).

ORYZA2000 follows the principles of the “School of de Wit” crop growth simulation models (Bouman et al., 1996). It simulates the growth and development of a rice crop in situations of potential production, water limitations, and nitrogen limitations (de Wit and Penning de Vries 1982). To simulate all these production situations, modules for above ground crop growth, evapotranspiration, nitrogen dynamics, soil-water balance and many more are combined in ORYZA2000 (Bouman et al., 2001). All these modules are programmed in the FORTRAN Simulation Environment (FSE) developed by (van Kraalingen, 1995).

The ORYZA2000 model follows a calculation scheme for the rate of dry mass production of the plant organs, and for the rate of phenological development. The rate of CO_2 assimilation is estimated from the daily incoming solar radiation, temperature, and leaf area index (LAI) by integrating instantaneous rates of leaf CO_2 assimilation over time and depth within canopy. The integration is based on an assumed sinusoidal time course of radiation over the day and the exponential extinction of radiation within the canopy.

The evapotranspiration (ET) module computes potential evaporation rates from soil and plant surfaces of the crop using any of three methods, viz., Penman, Priestley and Taylor, and Makkink, depending on the availability of meteorological data.

There are three soil-water balance modules in ORYZA2000: PADDY, SAHEL, SAWAH. PADDY is a one dimensional model that can be used for both puddled and non-puddled conditions in irrigated and rainfed environments (Wopereis et al., 1996). The model SAHEL (Soils in semi-Arid Habitats that Easily Leach) is of the so-called ‘tipping bucket type’ and was typically developed for freely-draining ‘upland’ soils with a deep groundwater table (Penning de Vries et al., 1989). SAWAH (Simulation Algorithm for Water flow in Aquic Habitats) can be used for both lowland and upland soils (ten Berge et al., 1992). Each water balance model has different data requirements. SAWAH has more detailed processes but the most data hungry module and requires detailed soil properties (viz. unsaturated hydraulic conductivity) which is more difficult to determine than other water balance model parameters.

3.4. Evaluation and application of ORYZA2000

ORYZA2000 has been successfully evaluated and applied in many parts of the rice-growing world including Iran (Amiri and Rezaei, 2010), Japan (Bannayan et al., 2005), China (Belder et al., 2005; Belder et al., 2007; Bouman et al., 2007b; Feng et al., 2007), Indonesia (Boling et al., 2007; Boling et al., 2010), and India (Arora, 2006; Das et al., 2007).

Feng et al. (2007) calibrated ORYZA2000 for low land and aerobic rice cultivars with data from field experiments in China and validated it successfully for a range of AWD (on SWT basis) treatments. Similarly, while evaluating ORYZA2000 against a range of AWD (1, 3, 5, 7, and 8 d irrigation intervals) treatments in Iran, Amiri (2008) found very good correlations between measured and simulated values.

ORYZA2000 has been used in a range of applications including prediction of: the effects of atmospheric CO_2 and fertilizer N management on rice growth (Bannayan et al., 2005), the effect of temperature on rice yield (Sheehy et al., 2006), the effect of groundwater depth on yield of rainfed lowland rice (Boling et al., 2007), and the impact of climate change on rice production (Das et al., 2007). ORYZA2000 has also been used in several studies to investigate water management for PTR in many locations, and for aerobic rice in China. In Punjab, India, Arora (2006) used ORYZA2000 to analyse the impacts of water management on rice yield, water use and water productivity. Using 12 years of weather data, they compared CF and AWD for PTR on a sandy loam soil. The AWD treatment involved CF for 2 weeks after transplanting, and thereafter irrigation (50 or 75 mm) 2 d after the disappearance of free water from the soil surface. AWD reduced the average (over 12 years) irrigation amount by about 350 mm or 25-30%, but ET was only reduced by about 30 mm. The WP_{ET} was about 5% lower with AWD, while WP_{I+R} was about 8%

higher with AWD due to reduced deep drainage. Belder et al. (2007) and Bouman et al. (2007b) also predicted only very small effects of AWD on ET from PTR using ORYZA2000 in the Philippines and China. The model predicted small to large effects of AWD on irrigation amount and deep drainage for a range of watertable depths and soil permeability. The reduction in irrigation with AWD was due to reduced drainage, and was highly dependent on rainfall, soil type and depth to the watertable.

In a scenario analysis using 34 years weather data of Beijing China, Xue et al. (2008) observed only a slight decline in the yield of the aerobic rice cultivar HD297 when the irrigation threshold increased from 10 kPa to 100 kPa SWT, however, there was sharp decline in the yield when SWT increased beyond 100kPa. ET was almost 700 mm when irrigation was scheduled at 10 kPa and declined sharply to around 500 mm at 20 kPa and then changed only slightly for thresholds up to 500 kPa. ET in purely rainfed conditions was in the range of 370-416 mm.

Based on research undertaken so far, it seems that ORYZA2000 is a suitable model for investigating the effects of establishment method and irrigation management on rice land and water productivity and water balance components under in the IGP.

4. Summary and knowledge gaps

Being the staple food of the majority of India’s people, rice is the most important crop in terms of food security. In India, food security is highly dependent on the rice-wheat cropping systems of north-west India. However, the productivity of rice-wheat cropping systems, and of rice in particular, is under major threat due to water scarcity, labour shortage and increasing production costs. Management strategies that reduce irrigation input, water depletion, labour requirement and production costs, and while maintaining or increasing crop yields, are urgently needed. Dry seeded rice appears to have exciting potential to address many of these constraints to rice production. But little is known about optimal water management for DSR, and its implications for water depletion and for WP_I, WP_{I+R} and WP_{ET} in comparison with PTR.

Field experiments can be used to help understand the interactions between establishment method and irrigation management on crop performance, water requirement and finally water productivity. However, field experiments require a lot of resources, so it is only possible to use field experiments to investigate a few factors under very limited site and seasonal conditions. While there have been many field experiments in north-west India in the past investigating the effects of changing from CF to AWD water management of PTR, this is not the case for DSR, and there have been very few comparisons of PTR and DSR as affected by water management, nor attempts to develop process understanding.

Crop models provide the ability to extrapolate the results of field experiments in space and time. Furthermore, crop models can be used to estimate components of water balance which are very difficult, expensive and time consuming to determine in the field. In addition, crop models provide the ability to predict probabilistic outcomes. There have been a few modelling studies on PTR in north-west India, but investigations on water management have been very limited, and there have been no modelling studies on DSR or its comparison with PTR as affected by water management. Therefore, the work presented in this thesis is designed to address following objectives:

i. To determine the effects of irrigation schedule on crop performance of DSR and PTR in field experiments in north-west India.
ii. To determine the water balance components and land and water productivity of DSR and PTR, as affected by irrigation schedule, in the field experiments.
iii. To use the results of the field experiments to calibrate and evaluate ORYZA2000 for DSR and PTR for north-west India.

iv. To use ORYZA2000 to evaluate the tradeoffs between yield, water depletion, WP_I and WP_{ET} as affected by establishment method and irrigation scheduling, using model simulations with 40 years of historic weather data.

v. To use the results of the field experiments and model simulations to identify the optimum establishment method × irrigation scheduling combinations.

5. Outline of the thesis

The starting point of this study was a comparison of PTR and DSR under a range of irrigation scheduling treatments. For this purpose, field experiments were conducted on the research farm of Punjab Agricultural University (PAU), Ludhiana, India. The next chapter (Chapter 2) describes the experiments and provides a detailed analysis of the crop performance of DSR and PTR under the different irrigation treatments. This is followed by an analysis and comparison of the soil water dynamics, components of the water balance, and water productivity in Chapter 3. Chapter 4 then presents the results of the calibration and evaluation of ORYZA2000 for PTR using data from the field experiments, followed by use of the model to simulate the effects of irrigation threshold on soil water dynamics, components of the water balance, and land and water productivity of PTR. The results of the calibration and evaluation of ORYZA2000 for DSR and model simulations are presented in Chapter 5, and the results of model simulations for DSR and PTR are used to examine the tradeoffs between yield, water depletion, WP_I and WP_{ET} as affected by establishment method and irrigation schedule. The thesis concludes in Chapter 6 where the main findings are summarised, and the implications of the thesis findings for science and its practical applications are presented, followed by recommendations for future research.

References

Adachi, K., 1992. Effect of puddling on rice-soil physics: softness of puddled soil and percolation. In: Murty, V.V.N., Koga, K. (Eds.), Soil and Water Engineering for Paddy Field Management. Asian Institute of Technology, Bangkok, Thailand, pp. 220-231.

Aggarwal, G.C., Sidhu, A.S., Sekhon, N.K., Sandhu, K.S., Sur, H.S., 1995. Puddling and N management effects on crop response in a rice-wheat cropping system. Soil Till. Res. 36, 129-139.

Ambast, S.K., Tyagi, N.K., Raul, S.K., 2006. Management of declining groundwater in the Trans Indo-Gangetic Plain (India): Some options. Agric. Water Manage. 82, 279-296.

Amiri, E., 2008. Evaluation of the rice growth model ORYZA2000 under water management. Asian J. Plant Sci. 7, 291-297.

Amiri, E., Rezaei, M., 2010. Evaluation of Water-Nitrogen Schemes for Rice in Iran, Using ORYZA2000 Model. Communications in Soil Sci. Plant Analy. 41, 2459-2477.

Arora, V.K., 2006. Application of a rice growth and water balance model in an irrigated semi-arid subtropical environment. Agric. Water Manage. 83, 51-57.

Arora, V.K., Gajri, P.R., Uppal, H.S., 2006. Puddling, irrigation, and transplanting-time effects on productivity of rice-wheat system on a sandy loam soil of Punjab, India. Soil Till. Res. 85, 212-220.

Bajpai, R.K., Tripathi, R.P., 2000. Evaluation of non-puddling under shallow water tables and alternative tillage methods on soil and crop parameters in a rice-wheat system in Uttar Pradesh. Soil Till. Res. 55, 99-106.

Balloli, S.S., Ratan, R.K., Garg, R.N., Singh, G., Krishnakumari, M., 2000. Soil physical and chemical environmental influenced by duration of rice-wheat cropping system. J. Indian Soc. Soil Sci. 48, 75-78.

Bannayan, M., Kobayashi, K., Kim, H.Y., Lieffering, M., Okada, M., Miura, S., 2005. Modeling the interactive effects of atmospheric CO2 and N on rice growth and yield. Field Crops Res. 93, 237-251.

Batta, R.K., Singh, S.R., Sharma, B.R., 1998. On-farm water management in major irrigation commands of India. Paper presented at the workshop on People's Participation in Irrigation Systems Management to Enhance Agricultural Production, 22-24 April 1998. Directorate of Water Management Research (ICAR). Patna, Bihar.

Belder, P., Bouman, B.A.M., Cabangon, R., Lu, G., Quilang, E.J.P., Li, Y.H., Spiertz, J.H.J., Tuong, T.P., 2004. Effect of water-saving irrigation on rice yield and water use in typical lowland conditions in Asia. Agric. Water Manage. 65, 193-210.

Belder, P., Bouman, B.A.M., Spiertz, J.H.J., 2007. Exploring options for water savings in lowland rice using a modelling approach. Agric. Syst. 92, 91-114.

Belder, P., Spiertz, J.H.J., Bouman, B.A.M., Lu, G., Tuong, T.P., 2005. Nitrogen economy and water productivity of lowland rice under water-saving irrigation. Field Crops Res. 93, 169-185.

Bhushan, L., Ladha, J.K., Gupta, R.K., Singh, S., Tirol-Padre, A., Saharawat, Y., Gathala, M., Pathak, H., 2007. Saving of water and labor in a rice-wheat system with no-tillage and direct seeding technologies. Agron. J. 99, 1288-1296.

Boling, A.A., Bouman, B.A.M., Tuong, T.P., Murty, M.V.R., Jatmiko, S.Y., 2007. Modelling the effect of groundwater depth on yield-increasing interventions in rainfed lowland rice in Central Java, Indonesia. Agric. Syst. 92, 115-139.

Boling, A.A., Tuong, T.P., van Keulen, H., Bouman, B.A.M., Suganda, H., Spiertz, J.H.J., 2010. Yield gap of rainfed rice in farmers' fields in Central Java, Indonesia. Agric. Syst. 103, 307-315.

Boonjung, H., Fukai, S., 1996. Effects of soil water deficit at different growth stages on rice growth and yield under upland conditions .1. Growth during drought. Field Crops Res. 48, 37-45.

Boparai, B.S., Yadvindersingh, Sharma, B.D., 1992. Effect of green manuring with *Sesbania aculeta* on physical properties of soil and on growth of wheat in rice-wheat and maize-wheat cropping systems in a semiarid region of India. Arid Soil Res. Rehabil. 6, 135-143.

Borrell, A., Garside, A., Fukai, S., 1997. Improving efficiency of water use for irrigated rice in a semi-arid tropical environment. Field Crops Res. 52, 231-248.

Bouman, B., Barker, R., Humphreys, E., Tuong, T.P., Atlin, G., Bennett, J., Dawe, D., Dittert, K., Dobermann, A., Facon, T., Fujimoto, N., Gupta, R., Haefele, S., Hosen, Y., Ismail, A., Johnson, D., Johnson, S., Khan, S., Shan, L., Masih, I., Matsuno, Y., Pandey, S., Peng, S., Thiyagarajan, T.M., Wassman, R. 2007a. Rice: feeding the billions. In: Molden, D. (Ed) Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. London: Earthscan, and Colombo: International Water Management Institute.

Bouman, B.A.M., Feng, L.P., Tuong, T.P., Lu, G.A., Wang, H.Q., Feng, Y.H., 2007b. Exploring options to grow rice using less water in northern China using a modelling approach - II. Quantifying yield, water balance components, and water productivity. Agric. Water Manage. 88, 23-33.

Bouman, B.A.M., Kropff, M.J., Tuong, T.P., Wopereis, M.C.S., ten Berge, H.F.M., Van Laar, H.H., 2001. ORYZA2000: Modelling Lowland Rice. International Rice Research Institute,Wageningen University and Research Centre, Los Baños, Philippines and Wageningen, Netherlands.

Bouman, B.A.M., Lampayan, R.M., Tuong, T.P., 2008. Water Management in Irrigated Rice: Coping with Water Scarcity. Interantional Rice Research Institute, Philippines, Los Baños, Philippines.

Bouman, B.A.M., Tuong, T.P., 2001. Field water management to save water and increase its productivity in irrigated lowland rice. Agric. Water Manage. 49, 11-30.

Bouman, B.A.M., vanKeulen, H., vanLaar, H.H., Rabbinge, R., 1996. The 'School of de Wit' crop growth simulation models: A pedigree and historical overview. Agric. Syst. 52, 171-198.

Bouman, B.A.M., Wopereis, M.C.S., Kropff, M.J., Tenberge, H.F.M., Tuong, T.P., 1994. Water-use efficiency of flooded rice fields. 2. Percolation and Seepage losses. Agric. Water Manage. 26, 291-304.

Budhar, M.S., Palaniappan, S.P., Rangaswamy, A., 1990. Performance of CR 666-18 rice under transplanted and direct seeded conditions. Oryza 27, 208-209.

Cabangon, R., Lu, G., Tuong, T.P., Bouman, B.A.M., Feng, Y., Zhang, Z.C., 2003. Irrigation Management Effects on Yield and Water Productivity of Inbred and Aerobic Rice Varieties in Kaifeng.

Cabangon, R.J., Tuong, T.P., Abdullah, N.B., 2002. Comparing water input and water productivity of transplanted and direct-seeded rice production systems. Agric. Water Manage. 57, 11-31.

Chahal, G.B.S., Sood, A., Jalota, S.K., Choudhury, B.U., Sharma, P.K., 2007. Yield, evapotranspiration and water productivity of rice (*Oryza sativa* L.)-wheat (*Triticum aestivum* L.) system in Punjab (India) as influenced by transplanting date of rice and weather parameters. Agric. Water Manage. 88, 14-22.

Cheng, Y., 1983. Drainage of paddy soils and its significance. Acta Pedologica Sinica 20, 215-224.

Choudhury, A.K., Saikia, M., Dutta, K., 1991. Effect of irrigation and nitrogen on transplanted summer rice yield and water use efficiency. Int. Rice Res. Notes 16, 18-19.

Choudhury, B.U., Bouman, B.A.M., Singh, A.K., 2007. Yield and water productivity of rice-wheat on raised beds at New Delhi, India. Field Crops Res. 100, 229-239.

Corton, T.M., Bajita, J.B., Grospe, F.S., Pamplona, R.R., Assis, C.A., Wassmann, R., Lantin, R.S., Buendia, L.V., 2000. Methane emission from irrigated and intensively managed rice fields in Central Luzon (Philippines). Nutr. Cycling Agroeco. 58, 37-53.

Das, L., Lohar, D., Sadhukhan, I., Khan, S.A., Saha, A., Sarkar, S., 2007. Evaluation of the performance of ORYZA2000 and assessing the impact of climate change on rice production in Gangetic West Bengal. J. Agromet. 9, 1-10.

Dawe, D., 2005. Increasing water productivity in rice-based systems in Asia - Past trends, current problems, and future prospects. Plant Prod. Sci. 8, 221-230.

De Dios, J., Corpuz, A.A., Espritu, A.J., Quilang, J.P., Malabayabas, M.D., 2000. Controlled irrigation on transplanted lowland rice for efficient use of irrigation water. Philippine Rice R&D highlights 1999. Department of Agriculture, Philippines Rice Research Institute, Maligaya, Muñoz, Nueva Ecija, pp. 51-52.

de Wit, C.T., Penning de Vries, F.W.T., 1982. L'anlyse des systemes de production primaire. In: Penning de Vries, F.W.T., Djiteye, M.A. (Eds.), La productivite des paturages saheliens. Une etude des sols, des vegetations et de 1'exploitation de cette resource naturelle., Wageningen, Netherland, pp. 20-27.

Dhillon, B.S., Kataria, P., Dhillon, P.K., 2010. National food security vis-a-vis sustainability of agriculture in high crop productivity regions. Current Sci. 98, 33-36.

Drenth, H., ten Berge, H.F.M., Riethoven, J.J.M., 1994. ORYZA simulation modules for potential and nitrogen limited rice production. SARP Research Proceedings, IRRI/AB-DLO, Wageningen, Netherlands, p. 223.

Evans, L.T., 1993. Crop Evolution, Adaptation and Yield. Cambridge University Press, Cambridge.

Feng, L.P., Bouman, B.A.M., Tuong, T.P., Cabangon, R.J., Li, Y.L., Lu, G.A., Feng, Y.H., 2007. Exploring options to grow rice using less water in northern China using a modelling approach - I. Field experiments and model evaluation. Agric. Water Manage. 88, 1-13.

Fukai, S., Rajatasereekul, S., Boonjung, H., Skulkhu, E., 1995. Simulation modelling to quantify the effect of drought for rainfed lowland rice in Northeast Thailand., In: Fragile lives in fragile ecosystems. Proceedings of the International Rice Research Conference. International Rice Research Institute, Los Baños, Philippines.

Gangwar, K.S., Tomar, O.K., Pandey, D.K., 2008. Productivity and economics of transplanted and direct-seeded rice (*Oryza sativa*) - based cropping systems in Indo-Gangetic plains. Indian J. Agric. Sci. 78, 655-658.

Garrity, D.P., Otoole, J.C., 1994. Screening rice for drought resistance at the reproductive phase. Field Crops Res. 39, 99-110.

Gaydon, D., Lisson, S., Xevi, E., 2006. Application of APSIM 'multi-paddock' to estimate whole-of-farm water-use efficiency, system water balance and crop production for a rice-based operation in the Coleambally Irrigation District, NSW. In: Turner, N., Acuna, T. (Eds.), Proceedings of the 13th Australian Agronomy Conference. 10-14 September 2006, Perth, Western Australia.

Gill, M.S., 2008. Productivity of direct-seeded rice (*Oryza sativa*) under varying seed rates, weed control and irrigation levels. Indian J. Agric. Sci. 78, 766-770.

Gill, M.S., Dhingra, K.K., 2002. Growing of basmati rice by direct seeding method in Punjab. Indian Farmer's Digest 13, 141.

Giri, G.S., 1998. Effect of rice and wheat establishment techniques on wheat yield. In: Hobbs, P.R., Bhandari, R. (Eds.), Proceedings of rice-wheat research end of project workshop, India, pp. 65-68.

Goel, A.C., Verma, K.S., 2000. Comparative study of direct seeding and transplanting of rice. Indian J. Agric. Res. 34, 194-196.

Hijmans, R.J., Guiking-Lens, I.M., van Diepen, C.A., 1994. WOFOST, user guide for the WOFOST 6.0 crop growth simulation model. Technical document 12, DLO Winand Staring Centre, Wageningen,The Netherlands.

Hira, G.S., 2009. Water management in northern states and the food security of India. J. Crop Improv. 23, 136-157.

Hira, G.S., Jalota, S.K., Arora, V.K., 2004. Efficient management of water resources for sustainable cropping in Punjab., Research Bulletin. Department of Soil, Punjab Agriucultural University, Ludhiana, Punjab, p. 20.

Hira, G.S., Rachhpal, S., Kukal, S.S., 2002. Soil matric suction: a criterion for scheduling irrigation to rice (Oryza sativa). Indian J. Agric. Sci. 72, 236-237.

Hobbs, P., Morris, M., 1996. Meeting South Asia's future food requirements for rice-wheat cropping: priority issues facing researchers in the post-green revolution era. NRG Paper No. 96-01, CIMMYT, Mexico DF, p. 46.

Hobbs, P.R., Gupta, R.K., 2002. Resource Conserving Technologies for Wheat in Rice-Wheat Systems. In: Ladha, J.K., James, E.H., Duxbury, J.D., Gupta, R.K., Buresh, R.J. (Eds.), Improving the productivity and sustainability of rice-wheat systems : issues and impacts. ASA sepecial publication, ASA, Madison, WI.

Hobbs, P.R., Singh, Y., Giri, G.S., Lauren, J.G., Duxbury, J.M., 2002. Direct-seeding and reduced-tillage options in the rice-wheat systems of the Indo-Gangetic Plains of South Asia. In: Pandey, S., Mortimer, M., Wade, L., Tuong, T.P., Lopez, K., Hardy, B. (Eds.), International workshop in direct seeding in Asian rice systems: strategies, research issues and opportunities. Los Baños (Philippines): International Rice Research Institute, Bangkok, Thialand, pp. 201-215.

Horie, T., Yajima, M., Nakagawa, H., 1992. Yield forecasting. Agric. Syst. 40, 211-236.

Humphreys, E., Kukal, S.S., Amanpreet, K., Sudhir, T., Sudhir, Y., Yadvinder, S., Balwinder, S., Timsina, J., Dhillon, S.S., Prashar, A., Smith, D.J., 2008. Permanent beds for rice-wheat systems in Punjab, India. 2: Water balance and soil water dynamics. ACIAR Proceedings Series, 37-61.

Humphreys, E., Kukal, S.S., Christen, E.W., Hira, G.S., Balwinder, S., Sudhir, Y., Sharma, R.K., 2010. Halting the groundwater decline in North-West India - which crop technologies will be winners? Adv. Agron. 109, 155-217.

Humphreys, E., Meisner, C., Gupta, R., Timsina, J., Beecher, H.G., Lu, T.Y., Yadvinder, S., Gill, M.A., Masih, I., Guo, Z.J., Thompson, J.A., 2005. Water saving in rice-wheat systems. Plant Prod. Sci. 8, 242-258.

Humphreys, E., Muirhead, W.A., Fawcett, B.J., Townsend, J.T., Murray, E.A., 1995. Puddling in mechanised rice culture: Impacts on water use and the productivity of rice and post-rice crops. In: Kirchhof, G., So, H.B. (Eds.), Management of Clay Soils for Rainfed Lowland Rice-Based Cropping Systems, pp. 213-218.

Iqbal, S., Ahmad, A., Hussain, A., Ali, M.A.T., Khaliq, T., Wajid, S.A., 2008. Influence of transplanting date and nitrogen management on productivity of paddy cultivars under variable environments. Int. J. Agric. Bio. 10, 288-292.

Jalota, S.K., Arora, V.K., 2002. Model-based assessment of water balance components under different cropping systems in north-west India. Agric. Water Manage. 57, 75-87.

Jalota, S.K., Singh, K.B., Chahal, G.B.S., Gupta, R.K., Chakraborty, S., Sood, A., Ray, S.S., Panigrahy, S., 2009. Integrated effect of transplanting date, cultivar and irrigation on yield, water saving and water productivity of rice (Oryza sativa L.) in Indian Punjab: Field and simulation study. Agric. Water Manage. 96, 1096-1104.

Jat, M.L., Gathala, M.K., Singh, K.K., Ladha, J.K., Singh, S., Gupta, R.K., Sharma, S.K., Saharawat, Y.S., 2008. Experiences with permanent beds in the rice–wheat systems of the western Indo-Gangetic plain. In: E. Humphreys, C.H. Roth (Eds.), Proceedings of the Workshop on Permanent Beds and Rice Residue Management for Rice–Wheat Systems in the Indo-Gangetic Plains, ACIAR No. 127. Australian Centre for International Agricultural Research, Canberra, Australia.

Jha, K.P., Chandra, D., Challaiah, 1981. Irrigation requirement of high-yielding rice varieties grown on soil having shallow water-table. Indian J. Agric. Sci. 51, 732-737.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. The DSSAT cropping system model. Eu. J. Agron. 18, 235-265.

Kato, Y., Okami, M., Katsura, K., 2009. Yield potential and water use efficiency of aerobic rice (Oryza sativa L.) in Japan. Field Crops Res. 113, 328-334.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M., Smith, C.J., 2003. An overview of APSIM, a model designed for farming systems simulation. Eu. J. Agron. 18, 267-288.

Khan, A.H., Alam, M., Ladha, J.K., 2003. Productivity evaluation of rice–wheat cropping system under new crop establishment technique. Paper presented at the FAO/IAEA Coordinated Research Project on Integrated Soil, Water and Nutrient Management for Sustainable Rice–Wheat Cropping System in Asia (IAEA, Vienna, Austria).Kirk, G., 2004. Biological processes in the soil and flood water. John Wiley and Sons, Chichester, UK.

Kreye, C., Bouman, B.A.M., Castaneda, A.R., Lampayan, R.M., Faronilo, J.E., Lactaoen, A.T., Fernandez, L., 2009. Possible causes of yield failure in tropical aerobic rice. Field Crops Res. 111, 197-206.

Kropff, M.J., Van Laar, H.H., Matthews, R.B., 1994. ORYZA1, an ecophysiological model for irrigated rice production. SARP Research Proceedings, AB-DLO, Wageningen, The Netherlands, p. 110.

Kukal, S.S., Aggarwal, G.C., 2002. Percolation losses of water in relation to puddling intensity and depth in a sandy loam rice (*Oryza sativa*) field. Agric. Water Manage. 57, 49-59.

Kukal, S.S., Aggarwal, G.C., 2003a. Puddling depth and intensity effects in rice-wheat system on a sandy loam soil I. Development of subsurface compaction. Soil Till. Res. 72, 1-8.

Kukal, S.S., Aggarwal, G.C., 2003b. Puddling depth and intensity effects in rice-wheat system on a sandy loam soil II. Water use and crop performance. Soil Till. Res. 74, 37-45.

Kukal, S.S., Hira, G.S., Sidhu, A.S., 2005. Soil matric potential-based irrigation scheduling to rice (Oryza sativa). Irri. Sci. 23, 153-159.

Kukal, S.S., Yadvinder-Singh, Sudhir-Yadav, Humphreys, E., Kaur, A., Thaman, S., 2008. Why grain yield of transplanted rice on permanent raised beds decline over time? Soil Till. Res. 99, 261-67.

Kumar, V., Bellinder, R.R., Gupta, R.K., Malik, R.K., Brainard, D.C., 2008. Role of herbicide-resistant rice in promoting resource conservation technologies in rice-wheat cropping systems of India: A review. Crop Prot. 27, 290-301.

Ladha, J.K., Dawe, D., Pathak, H., Padre, A.T., Yadav, R.L., Singh, B., Singh, Y., Singh, P., Kundu, A.L., Sakal, R., Ram, N., Regmi, A.P., Gami, S.K., Bhandari, A.L., Amin, R., Yadav, C.R., Bhattarai, E.M., Das, S., Aggarwal, H.P., Gupta, R.K., Hobbs, P.R., 2003a. How extensive are yield declines in long-term rice-wheat experiments in Asia? Field Crops Res. 81, 159-180.

Ladha, J.K., Fischer, K.S., Hossain, M., Hobbs, P.R., Hardy, B., 2000. Improving the productivity and sustainability of rice-wheat systems of the Indo-Gangetic Plains: a synthesis of NARS-IRRI partnership research., IRRI Discussion Paper Series No. 40., Los Baños (Philippines): International Rice Research Institute, p. 31.

Ladha, J.K., Pathak, H., Gupta, R.K., 2007. Sustainability of the rice-wheat cropping system: issues, constraints and remedial options. J. Crop Improv. 19, 125-136.

Ladha, J.K., Pathak, H., Tirol-Padre, A., Dawe, D., Gupta, R.K., 2003b. Productivity trends in intensive rice-wheat cropping systems in Asia. In: Ladha, J.K., Hill, J.E., Duxbury, J.M., Gupta, R.K., Buresh, R.J. (Eds.), Improving the Productivity and Sustainability of Rice-Wheat Systems: Issues and Impacts. ASAInc, CSSAInc, SSSAInc, Madison, USA, pp. 45-76.

Lal, R., Griffin, M., Apt, J., Lave, L., Morgan, M.G., 2004. Ecology - Managing soil carbon. Sci. 304, 393-393.

Li, Y.H., 2001. Research and practice of water saving irrigation for rice in China. In: Barker, R., Loeve, R., Li, Y., Tuong, T.P. (Eds.), Proceedings of an International Workshop on Water-Saving Irrigation for Rice, Wuhan, China, pp. 135-144.

Lu, W.F., Chen, W., Duan, B.W., Guo, W.M., Lu, Y., Lantin, R.S., Wassmann, R., Neue, H.U., 2000. Methane emissions and mitigation options in irrigated rice fields in southeast China. Nutrient Cycling in Agroecosystems 58, 65-73.

Mahajan, G., Bharaj, T.S., Timsina, J., 2009. Yield and water productivity of rice as affected by time of transplanting in Punjab, India. Agric. Water Manage. 96, 525-532.

Malik, R.K., Yadav, A., Gill, G.S., Sardana, P., Gupta, R.K., Piggin, C., 2004. Evolution and acceleration of no-till farming in rice–wheat cropping system of the Indo-Gangetic plains. New Directions for a Diverse Planet. Proceedings of the Fourth International Crop Science Congress, 26 September–1 October 2004. Brisbane, Australia. Published on CDROM. http://www.cropscience.org.au.

Malik, R.K., Yadav, A., Singh, S., 2005. Resource conservation technologies in rice-wheat cropping system of Indo-Gangetic Plain. In: Abrol, L.P., Gupta, R.K., Malik, R.K. (Eds.), Conservation Agriculture-Status and Prospects., Centre for Advancement of Sustainable Agriculture, New Delhi, India, pp. 13-22.

Mangat, R., Hari, O., Dhiman, S.D., Nandal, D.P., 2006. Productivity and economics of rice (*Oryza sativa*)-wheat (*Triticum aestivum*) cropping system as affected by establishment methods and tillage practices. Indian J. Agron. 51, 77-80.

Mao, Z., Li, Y., Tuong, T.P., Molden, D., Dong, B., 2000. Water-efficient irrigation regimes of rice in China. Paper presented at the International Rice Research Conference, Los Baños, Philippines.

McMennamy, J.A., O'Toole, J.C., 1983. RICEMOD: a physiologically based rice growth and yield model. International Rice Research Institute, Los Banos (Philippines), p. 33.

Metschies, G.P., 2005. International fuel prices-2005, 4th Edition. German technical Cooperation, Division 44-Environment and Infrastructure, p. www.internationalfuelprices.com.

Mishra, H.S., Rathore, T.R., Pant, R.C., 1990. Effect of intermittent irrigation on groundwater table contribution, irrigation requirement and yield of rice in mollisols of the Tarai region. Agric. Water Manage. 18, 231-241.

Mosier, A.R., Duxbury, J.M., Freney, J.R., Heinemeyer, O., Minami, K., 1998. Assessing and mitigating N2O emissions from agricultural soils. Climatic Change 40, 7-38.

Ortiz-Monasterio, J.I., Dhillon, S.S., Fischer, R.A., 1994. Date of sowing effects on grain yield and yield components of irrigated spring wheat cultivars and relationship with radiation and temperature in Ludhiana, India. Field Crops Res. 37, 169-184.

O'Toole, J.C., Moya, T.B., 1981. Water deficits and yield in upland rice. Field Crops Res. 4, 247-259.

Pandey, S., Velasco, L., 1999. Economics of direct seedling in Asia. Patterns of adoption and research priorities. Int. Rice Res. Newslet. 24, 6-11.

Pandey, S., Velasco, L., 2005. Trends in crop establishment methods in Asia and research issues. In: Toriyama, K., Heong, K.L., Hardy, B. (Eds.), Rice is Life: Scientific

Perspectives for the 21st Century, Proceedings of the World Rice Research Conference. Los Baños (Philippines): International Rice Research Insititute, and Tsukuba (Japan): Japan International Research Centre for Agricultural Science., Tokyo and Tsukuba, Japan, pp. 178-181.

Parihar, S.S., 2004. Effect of crop-establishment method, tillage, irrigation and nitrogen on production potential of rice (*Oryza sativa*)-wheat (*Triticum aestivum*) cropping system. Indian J. Agron. 49, 1-5.

Pathak, H., Ladha, J.K., Aggarwal, P.K., Peng, S., Das, S., Singh, Y., Singh, B., Kamra, S.K., Mishra, B., Sastri, A., Aggarwal, H.P., Das, D.K., Gupta, R.K., 2003. Trends of climatic potential and on-farm yields of rice and wheat in the Indo-Gangetic Plains. Field Crops Res. 80, 223-234.

Pathak, H., Li, C., Wassmann, R., 2005. Greenhouse gas emissions from Indian rice fields: calibration and upscaling using the DNDC model. Biogeosciences 2, 113-123.

Penning de Vries, F.W.T., Jansen, D.M., ten Berge, H.F.M., Bakema, A., 1989. Simulation of Ecophysiological Processes of Growth in Several Annual Crops., Pudoc, Wageningen, The Netherlands.

Ponnamperuma, F.N., 1972. The chemistry of submerged soils. Adv. Agron. 24, 29-96.

Raina, R.S., Sangar, S., 2004. Institutional reform in knowledge for integrated water management – groundwater lessons from Haryana. In: Abrol, I.P., Sharma, B.R., Sekhon, G.S. (Eds.), Groundwater Use in NorthWest India – Workshop Paper. Centre for Advancement of Sustainable Agriculture, New Delhi, India, pp. 178-193.

Rodell, M., Velicogna, I., Famiglietti, J.S., 2009. Satellite-based estimates of groundwater depletion in India. Nature 460, 999-U980.

Saharawat, Y.S., Gathala, M., 2011. Water management of rice in western and eastern IGP. Towards double zero till for rice-wheat system in Indo-Gangetic Plain, 13-14 February, New Delhi, India.

Saharawat, Y.S., Gathala, M., Ladha, J.K., Malik, R.K., Singh, S., Jat, M.L., Gupta, R.K., Pathak, H., Singh, K., 2009. Evaluation and promotion of integrated crop and resource management in the rice-wheat system in north-west India. In: Ladha, J.K., Yadvinder-Singh, Erenstein, O., Hardy, B. (Eds.), Integrated crop and resource management in the rice-wheat system of South Asia. Los Baños (Philippines): International Rice Research Institute, pp. 133-150.

Saharawat, Y.S., Singh, B., Malik, R.K., Ladha, J.K., Gathala, M., Jat, M.L., Kumar, V., 2010. Evaluation of alternative tillage and crop establishment methods in a rice-wheat rotation in North Western IGP. Field Crops Res. 116, 260-267.

Sattar, M.A., 1992. Water management and technology adoption for direct seeded rice in an irrigation system. Central Luzon State University, Philippines, p. 174.

Shah, T., Scott, C., Kishore, A., Sharma, A., 2003. Energy-irrigation nexus in South Asia: Improving groundwater conservation and power sector viability. International Water Management Institute, Colombo, Sri Lanka.

Sharma, P.K., Bhushan, L., Ladha, J.K., Naresh, R.K., Gupta, R.K., Balasubramanian, B.V., Bouman, B.A.M., 2002. Crop-water relation in rice–wheat cropping under different tillage systems and water management practice in a marginally sodic, medium textured soils. In: Bouman, B.A.M., Hengsdijk, H., Hardy, B., Toung, T.P., Ladha, J.K. (Eds.), Water-wise Rice Production. Los Ban˜os, Philippines, pp. 223–235.

Sharma, P., Tripathi, R.P., Singh, S., 2005. Tillage effects on soil physical properties and performance of rice-wheat-cropping system under shallow water table conditions of Tarai, Northern India. Eu. J. Agron. 23, 327-335.

Sharma, P., Tripathi, R.P., Singh, S., Kumar, R., 2004. Effects of tillage on soil physical properties and crop performances under rice-wheat system. Indian Soc. Soil Sci. 52, 12-16.

Sharma, P.K., Dedatta, S.K., 1986. Physical properties and processes of puddle rice soils. Adv. Soil Sci. 5, 139-153.

Sheehy, J.E., Mitchell, P.L., Ferrer, A.B., 2006. Decline in rice grain yields with temperature: Models and correlations can give different estimates. Field Crops Res. 98, 151-156.

Singh, A.K., Choudhury, B.U., Bouman, B.A.M., 2002. Effects of rice establishment methods on crop performance, water use, and mineral nitrogen. In: Bouman, B.A.M., Hengsdijk, H., Hardy, B., Bindraban, B., Tuong, T.P., Ladha, J.K. (Eds.), Proceedings of the International Workshop on Water-wise Production. International Rice Research Institute, Los Baños, Philippines, pp. 237-246.

Singh, K.B., Gajri, P.R., Arora, V.K., 2001a. Modelling the effects of soil and water management practices on the water balance and performance of rice. Agric. Water Manage. 49, 77-95.

Singh, S., Sharma, S.N., Prasad, R., 2001b. The effect of seeding and tillage methods on productivity of rice-wheat cropping system. Soil Till. Res. 61, 125-131.

Singh, R., Gajri, P.R., Gill, K.S., Khera, R., 1995. Puddling intensity and nitrogen-use efficiency of rice (*Oryza sativa*) on a sandy-loam soil of Punjab. Indian J. Agric. Sci. 65, 749-751.

Singh, S., Bhushan, L., Ladha, J.K., Gupta, R.K., Rao, A.N., Sivaprasad, B., 2006. Weed management in dry-seeded rice (*Oryza sativa*) cultivated in the furrow-irrigated raised-bed planting system. Crop Prot. 25, 487-495.

Singh, S., Tripathi, R.P., Sharma, P., Kumar, R., 2004. Effect of tillage on root growth, crop performance and economics of rice (Oryza sativa)-wheat (*Triticum aestivum*) system. Indian J. Agric. Sci. 74, 300-304.

Singh, U.P., Singh, Y., Virender-Kumar, Ladha, J.K., 2009a. Evaluation and promotion of resource-conserving tillage and crop establishment techniques in the rice-wheat system of eastern India. In: Ladha, J.K., Yadvinder-Singh, Erenstein, O., Hardy, B. (Eds.), Integrated crop and resource management in the rice-wheat system of South Asia. International Rice Research Institute, Los Baños, Philippines, pp. 151-176.

Singh, V.P., Singh, G., Singh, S.P., Kumar, A., Singh, Y., Johnson, D.E., 2008. Direct seeding and weed management in the irrigated rice-wheat production system. In: Singh, Y., Singh, V.P., Chauhan, B., Orr, A., Mortimer, A.M., Johnson, D.E., Hardy, B. (Eds.), Direct seeding and weed management in the irrigated rice-wheat cropping system of the Indo-Gangetic Plains. Los Baños (Philippines): International Rice Research Institute and Pantnagar (India):Directorate of Experiment Station, G.B. Pant University of Agriculture and Technology, pp. 131-138.

Singh, Y., Humphreys, E., Kukal, S.S., Singh, B., Kaur, A., Thaman, S., Prashar, A., Yadav, S., Timsina, J., Dhillon, S.S., Kaur, N., Smith, D.J., Gajri, P.R., 2009b. Crop performance in permanent raised bed rice-wheat cropping system in Punjab, India. Field Crops Res. 110, 1-20.

Soylu, M.E., Istanbulluoglu, E., Lenters, J.D., Wang, T., 2011. Quantifying the impact of groundwater depth on evapotranspiration in a semi-arid grassland region. Hydrol. Earth Syst. Sci. 15, 787-806.

Tabbal, D.F., Bouman, B.A.M., Bhuiyan, S.I., Sibayan, E.B., Sattar, M.A., 2002. On-farm strategies for reducing water input in irrigated rice; case studies in the Philippines. Agric. Water Manage. 56, 93-112.

Takshi, K.S., Chopra, R.P.S., 2004. Monitoring and assessment of groundwater resources in Punjab State. In: Abrol, I.P., Sharma, B.R., Sekhon, G.S. (Eds.), Groundwater Use in North-West India – Workshop Paper. Centre for Advancement of Sustainable Agriculture, New Delhi, India, pp. 8-15.

ten Berge, H.F.M., Jansen, D.M., Rappoldt, C., Stol, W., 1992. The soil water balance module SAWAH: user's guide and outline. CABO-TPE Simulation Report Series, no. 22, ABO, Wageningen, The Netherlands, p. 78.

ten Berge, H.F.M., Kropff, M.J., 1995. Founding a systems research network for rice. In: Bouma, J., Kuyvenhoven, A., Bouman, B.A.M., Luyten, J.C., Zandstra, H.G. (Eds.), Eco-regional Approaches for Sustainable Land Use and Food Production. Kluwer Academic Publishers, Dordrecht, pp. 263-282.

Timsina, J., Connor, D.J., 2001. Productivity and management of rice-wheat cropping systems: Issues and challenges. Field Crops Res. 69, 93-132.

Timsina, J., Humphreys, E., 2006. Performance of CERES-Rice and CERES-Wheat models in rice-wheat systems: A review. Agric. Syst. 90, 5-31

Tripathi, R.P., Sharma, P., Singh, S., 2005a. Tilth index: an approach to optimize tillage in rice-wheat system. Soil Till. Res. 80, 125-137.

Tripathi, S.C., Mongia, A.D., Shoran, J., 2005b. Resource conservation technologies and cropping system diversification opportunities. In: Abrol, L.P., Gupta, R.K., Malik, R.K. (Eds.), Conservation Agriculture-Status and Prospects, Centre for Advancement of Sustainable Agriculture, New Delhi, India, pp. 72-78

Tuong, T.P., 1999. Productive water use in rice production: opportunities and limitations for water use in crop production. J. Crop Prod. 2, 241-264.

Tuong, T.P., Wopereis, M.C.S., Marquez, J.A., Kropff, M.J., 1994. Mechanism and control of percolation losses in irrigated puddled rice field. Soil Sci. Soc. Am. J. 58, 1794-1803.

Tuong, T.P., Cabangon, R.J., Wopereis, M.C.S., 1996. Quantifying flow processes during land soaking of cracked rice soils. Soil Sci. Soc. Am. J. 60, 872-879.

Tyagi, N.K., Agrawal, A., Sakthivadivel, R., Ambast, S.K., 2005. Water management decisions on small farms under scarce canal water supply: A case study from NW India. Agric. Water Manage. 77, 180-195.

UNESCO, 1995. "United Nations Educational, Scientific, and Cultural Organization (UNESCO) Statistical Yearbook 1995". UNESCO, Paris, France.

Van Keulen, H., Wolf, J., 1986. Modelling of Agricultural Production: Weather, Soils and Crops Simulation Monographs., Pudoc, Wageningen, The Netherlands.

van Kraalingen, D.W.G., 1995. The FSE system for crop simulation: version 2.1. Quantitative Approaches in Systems Analysis Report 1. Wageningen (Netherland). C.T. de Wit Graduate School for Production Ecology and AB-DLO, p. 58.

Vijayakumar, M., Ramesh, S., Chandrasekaranand, B., Thiyagarajan, T.M., 2006. Effect of System of Rice Intensification (SRI) practices on yield attributes, yield and water productivity of rice (*Oryza Sativa*). Res. J. Agric. Bio. Sci. 2, 236-242.

Wang, G., 1999. Techniques of shallow-exposed irrigation of rice and its popularization. In: Xu, Z. (Ed.), Proceedings of the International Symposium on Water-Saving Irrigation for Paddy Rice, Guilin, China, pp. 47-53.

Wassmann, R., Neue, H.U., Ladha, J.K., Aulakh, M.S., 2004. Mitigating greenhouse gas emissions from rice–wheat cropping system in Asia. Environment, Development and Sustainability 6, 65-90.

Wickham, T.H., Singh, V.P., 1978. Water movement through wet soils. Soil and rice. International Rice Research Institute, Los Baños (Philippines), pp. 337-358.

Won, J.G., Choi, J.S., Lee, S.P., Son, S.H., Chung, S.O., 2005. Water saving by shallow intermittent irrigation and growth of rice. Plant Prod. Sci. 8, 487-492.

Wopereis, M.C.S., Bouman, B.A.M., Tuong, T.P., ten Berge, H.F.M., Kropff, M.J., 1996. ORYZA_W:rice growth model for irrigated and rainfed environment., SARP Research Proceedings, Wageningen (Netherlands):IRRI/AB-DLO, p. 159.

Wu, X., 1999. Popularization of water saving irrigation techniques to farmers. In: Xu, Z. (Ed.), Proceedings of the international symposium on water-saving irrigation for paddy, Guilin, China, pp. 41-46.

Xue, C.Y., Yang, X.G., Bouman, B.A.M., Deng, W., Zhang, Q.P., Yan, W.X., Zhang, T.Y., Rouzi, A., Wang, H.Q., 2008. Optimizing yield, water requirements, and water productivity of aerobic rice for the North China Plain. Irrig. Sci. 26, 459-474.

Yadav, D.S., Sushant, Mortimer, A.M., Johnson, D.E., 2008. Studies on direct seeding of rice, weed control and tillage practices in the rice-wheat cropping system in eastern Uttar Pradesh. In: Singh, Y., Singh, V.P., Chauhan, B., Orr, A., Mortimer, A.M., Johnson, D.E., Hardy, B. (Eds.), Direct seeding and weed management in the irrigated rice-wheat cropping system of the Indo-Gangetic Plains. Los Baños (Philippines): International Rice Research Institute and Pantnagar (India):Directorate of Experiment Station, G.B. Pant University of Agriculture and Technology, pp. 139-150.

Yadvinder-Singh, Bijay-Singh, Nayyar, V.K., Jagmohan-Singh, 2003. Nutrient management for sustainable rice-wheat cropping system. National Agricultural Technology Project. Indian Council of Agricultural Research, New Delhi, India, and Punjab Agricultural University, Ludhian, Punjab, India.

Yang, J.C., Liu, K., Wang, Z.Q., Du, Y., Zhang, J.H., 2007. Water-saving and high-yielding irrigation for lowland rice by controlling limiting values of soil water potential. J. Integrative Plant Bio. 49, 1445-1454.

Yi, Y., 1999. Shallow-exposed irrigation and irrigation of rice without water layer. In: Xu, Z. (Ed.), Proceedings of the International Symposium on Water-Saving Irrigation for Paddy Rice, Guilin, China, pp. 163-167.

Zhang, X., Lee, J.H., Abawi, Y., Kim, Y.H., McClymont, D., Kim, H.D., 2007. Testing the simulation capability of APSIM-ORYZA under different levels of nitrogen fertiliser and transplanting time regimes in Korea. Australian J. Exp. Agric. 47, 1446-1454.

Zhang, H., Xue, Y.G., Wang, Z.Q., Yang, J.C., Zhang, J.H., 2009. An Alternate Wetting and Moderate Soil Drying Regime Improves Root and Shoot Growth in Rice. Crop Sci. 49, 2246-2260.

Zhang, H., Zhang, S.F., Yang, J.C., Zhang, J.H., Wang, Z.Q., 2008. Postanthesis moderate wetting drying improves both quality and quantity of rice yield. Agron. J. 100, 726-734.

Chapter 2

EFFECT OF WATER MANAGEMENT ON DRY SEEDED AND PUDDLED TRANSPLANTED RICE. PART 1: CROP PERFORMANCE

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Field Crops Research 120 (1), 112-122

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Sudhir-Yadava, Gill, G., Humphreys, E., Kukal, S.S. & Walia, U.S. (2011) Effect of water management on dry seeded and puddled transplanted rice. Part 1: Crop performance
Field Crops Research, v. 120 (1), pp. 112-122

NOTE:
This publication is included on pages 48 - 58 in the print copy of the thesis held in the University of Adelaide Library.

It is also available online to authorised users at:

http://dx.doi.org/10.1016/j.fcr.2010.09.002

Chapter 3

EFFECT OF WATER MANAGEMENT ON DRY SEEDED AND PUDDLED TRANSPLANTED RICE. PART 2: WATER BALANCE AND WATER PRODUCTIVITY

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Field Crops Research 120 (1), 123-132

NOTE:
Statements of authorship appear in the print copy of the thesis held in the University of Adelaide Library.

Sudhir-Yadava, Humphreys, E., Kukal, S.S., Gill, G. & Rangarajan, R. (2011) Effect of water management on dry seeded and puddled transplanted rice. Part 2: Water balance and water productivity
Field Crops Research, v. 120 (1), pp. 123-132

NOTE:
This publication is included on pages 61 - 70 in the print copy of the thesis held in the University of Adelaide Library.

It is also available online to authorised users at:

http://dx.doi.org/10.1016/j.fcr.2010.09.003

Chapter 4

EVALUATION AND APPLICATION OF ORYZA2000 FOR IRRIGATION SCHEDULING OF PUDDLED TRANSPLANTED RICE IN NORTH WEST INDIA

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Field Crops Research 122 (2), 104-117

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Statements of authorship appear in the print copy of the thesis held in the University of Adelaide Library.

Sudhir-Yadava, Li, T., Humphreys, E., Gill, G. & Kukal, S.S. (2011) Evaluation and application of ORYZA2000 for irrigation scheduling of puddled transplanted rice in north-west India
Field Crops Research, v. 122 (2), pp. 104-117

NOTE:
This publication is included on pages 73 - 84 in the print copy of the thesis held in the University of Adelaide Library.

It is also available online to authorised users at:

http://dx.doi.org/10.1016/j.fcr.2011.03.004

Chapter 5

EVALUATION OF TRADEOFFS IN LAND AND WATER PRODUCTIVITY OF RICE AS AFFECTED BY ESTABLISHMENT METHOD AND IRRIGATION SCHEDULE

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Field Crops Research 2011, Submitted Paper

Evaluation of tradeoffs in land and water productivity of rice as affected by establishment method and irrigation schedule

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Abstract

Management strategies that increase water productivities and reduce labour requirement while maintaining or increasing land productivity are urgently needed. Dry seeded rice (DSR) has been proposed as one of the technology to achieve these objectives but little is known about tradeoffs in land and water productivity of rice as affected by establishment method and irrigation schedule. This study tested the ability of the ORYZA2000 model to simulate effect of DSR on rice yield, water productivities and soil water dynamics under different thresholds of irrigation and then compared it with PTR under same criteria of irrigation. The study shows that under conditions of no or mild water stress (up to 20 kPa SWT) ORYZA2000 performs well in simulating the effects of irrigation schedule on crop growth, yield, water balance components and water productivity of both DSR and PTR in north-west India. However, the model over predicted crop growth and yield at higher irrigation thresholds (40 and 70 kPa), more so with DSR.

The scenario analysis for 40 rice seasons predicted that yield of DSR was slightly higher than PTR, more so with continuous flooding (CF) (by about 4%) and an irrigation threshold of 10 kPa. Yield of both PTR and DSR declined gradually, at about the same rate, as the irrigation threshold increased. In both establishment methods, there was large irrigation water saving when changing from CF to alternate wetting and drying (AWD), and only a small rate of decline in irrigation input as the threshold increased from 10 to 70 kPa. The water saving in AWD was primarily because of less drainage. The ET was about 100 mm higher in DSR than respective irrigation treatments of PTR, due to the longer duration of DSR in the main field. There were tradeoffs between yield, water

productivity and water depletion. Maximum yield occurred with DSR-CF, maximum WP_I with DSR with an irrigation threshold of 30 kPa, maximum WP_{ET} with PTR-20 kPa, and minimum ET in PTR with thresholds ≥20 kPa.

Keywords

ORYZA2000; Dry seeded rice; Alternate wetting and drying; Water saving; Soil water dynamics

Introduction

Puddling, followed by hand-transplanting of rice seedlings and continuous flooding, is the traditional method of rice culture in the Indo-Gangetic Plains (IGP) of South Asia. This establishment method consumes a lot of energy (for intensive tillage), labour and water. In north-west India, where agriculture is highly dependent upon migrant labour, labour scarcity for rice transplanting is now a major concern for the viability of puddled transplanted rice (PTR), and labour costs for hand transplanting have risen sharply in recent years. Another serious issue with traditional rice production is the very high water input, with very heavy reliance on groundwater for rice cultivation in north-west India. Farmers often have to use 100-250 mm (Tuong, 2000; Sudhir-Yadav et al., 2011b) of water just for the puddling operation before hand-transplanting. The high water requirement of rice is one of the reasons for the alarming rate of decline of the water table (30-100 cm per year) in some areas of north-west India (Hira and Khera, 2000; Hira et al., 2004; Ambast et al., 2006; Hira, 2009). The fall in groundwater is of concern to farmers because of the costs of deepening tubewells and installing pumps able to lift water from deeper depths. Secondly, groundwater is largely pumped using electricity, which is free or highly subsidised for farmers. The inadequate and unreliable electricity supply to rural areas is driving farmers to adopt more water use efficient methods of rice production.

Many farmer trials and experiments have shown that rice can be successfully dry seeded into non-puddled soils in the north-west IGP, with or without prior cultivation (Hobbs et al., 2002; Qureshi et al., 2004; Saharawat et al., 2009; Saharawat et al., 2010; Sudhir-Yadav et al., 2011a). Dry seeded rice (DSR) provides an opportunity for more timely crop establishment in some regions, and eliminates puddling from the rice-wheat cropping system, to the benefit of wheat and other upland crops in the rotation (Ladha et al., 2003). Moreover, DSR involves less intensive tillage than puddling, reducing fuel costs and generation of carbon dioxide, and is conducive to mechanisation of crop establishment (Khade et al., 1993), greatly reducing labour requirement. Studies in north-west India (Bhushan et al., 2007; Choudhury et al., 2007; Sudhir-Yadav et al., 2011b) have shown that DSR consumes less irrigation water than PTR when using the same irrigation scheduling criteria. However, yield of DSR in comparison to PTR is variable. Several studies in north-west India found similar yield of DSR and PTR (Gill, 2008; Saharawat et al., 2009; Sudhir-Yadav et al., 2011a). In contrast, other studies in the same region reported lower yield of DSR than PTR (Gupta et al., 2003; Sharma et al., 2005; Bhushan et al., 2007; Choudhury et al., 2007). The cause of the lower yields is generally unknown, but in some situations it was associated with weed infestation, micro-nutrient deficiency, nematodes and water stress (Singh et al., 2008; Kreye et al., 2009; Sudhir-Yadav et al., 2011a). Whether or how much of the yield loss was due to water deficit stress is unknown. The results of Sudhir-Yadav et al. (2011a) on a clay loam soil at Ludhiana showed that both PTR and DSR are extremely sensitive to water deficit stress, with yields declining as the threshold for irrigation decreased beyond a soil tension of 20 kPa at 18-20 cm soil depth. DSR was more sensitive to water deficit stress than PTR. These results were obtained in years of average or above average rainfall, and therefore the soil only dried to 20 kPa on a few occasions. Other studies suggest that the safe threshold for irrigation of PTR is 10 kPa (Bouman and Tuong, 2001). To date, there are no scientifically based guidelines for irrigation management for DSR, and the irrigation requirement for maximum yield will vary with site conditions (e.g. soil type, weather, depth to the watertable), variety, growth stage and management. Furthermore, there are few comparisons of DSR and PTR as affected by irrigation management.

Crop growth simulation models are useful tools for extrapolation of the results of field experiments on the effects of alternative management practices across different seasonal and agro-ecological conditions. Modelling studies can help explore establishment method and irrigation management for optimizing water and land productivity, and to determine the likely irrigation water savings. Determining the nature of the irrigation water savings is important to understand the effects of changed management on water depletion from the soil/groundwater system, and water availability for alternative uses. Modelling also studies provide an opportunity to estimate components of the water balance, most of which are very difficult to determine under field conditions. In the past, there have been several modelling studies in north-west India which explored the effects of various management practices on yield and water productivity of PTR (Arora, 2006; Chahal et al., 2007; Jalota et al., 2009; Sudhir-Yadav et al., 2011b). However, to date, there are no reports of the parameterization and evaluation of crop models for DSR in north-west India, nor in South Asia as a whole. Nor are there modelling studies comparing the performance of DSR and PTR, as affected by irrigation management.

Therefore, this study aimed to calibrate and evaluate the ORYZA2000 model for DSR, and to use the model to compare the effects of irrigation threshold on land and water productivity of DSR and PTR.

2. Materials and methods

2.1 Field experiment

Data from replicated field experiments were used to parameterize and evaluate the performance of the ORYZA2000 (V 2.13) model for PTR and DSR using the variety PAU201. The experiments were conducted during 2008 and 2009 at Punjab Agricultural

University (PAU) research farm, Ludhiana, India (30°54’ N, 75°98’E, 247 m AMSL) on a clay loam soil. Soil properties, crop management and crop and water monitoring methods are fully described in Sudhir-Yadav et al. (2011a,b).

The field experiments compared PTR and DSR with 4 irrigation schedules viz. (i) “daily” irrigation, and intermittent (AWD) irrigation when the soil water tension (SWT) at 20 cm depth increased to (ii) 20, (iii) 40 and (iv) 70 kPa. The DSR and the seed bed for PTR were sown on the same day (9 June each year). For the first 42 DAS, the DSR was irrigated to keep the soil water tension below 10-15 kPa at 10 cm soil depth, after which the irrigation treatments were commenced. The PTR was topped up daily to 50 mm standing water depth for the first 15 days after transplanting (DAT), prior to commencing the irrigation treatments. The daily irrigated treatments were topped up to 50 mm standing water depth throughout the season, until about two weeks before harvest maturity. The amount of irrigation water applied to all AWD treatments was 50 mm at each irrigation.

2.2. ORYZA2000 model

2.2.1. Parameterization and validation

The results of the model parameterization and validation for PTR are presented in Sudhir-Yadav et al. (2011c). The same methodology was used to parameterize and evaluate the model for DSR, and only those parameters which differed for DSR and PTR are specified here. The SWIRTRF, which scales the transpiration changes under drought stress, was set to 0.025597 and 0.015597 in 2008 and 2009, respectively for DSR while it was 0.015597 (in 2008) and 0.010597 (in 2009) for PTR. Crop development rates were calculated using observed crop phenology parameters (Table 1; Table 1 in Sudhir-Yadav at al., 2011c for PTR). Similar to PTR, the measured saturated hydraulic conductivity (Ks) of the plough sole was further fine tuned by model fitting against measured soil water tension of DSR

(Table 2). The van Genuchten parameters were derived from the soil particle size analysis and organic matter content.

Table 1. Effect of irrigation schedule on crop growth stages of DSR in field experiments

Year	Irrigation treatment	Sowing	Emergence	Panicle initiation	Flowering	Physio. maturity	Harvest
2008	Daily	09 June	12 June	17 Aug.	17 Sept.	14 Oct.	21 Oct.
	20 kPa	09 June	12 June	22 Aug.	25 Sept.	23 Oct.	30 Oct.
	40 kPa	09 June	12 June	25 Aug.	30 Sept.	26 Oct.	03 Nov.
	70 kPa	09 June	12 June	25 Aug.	30 Sept.	26 Oct.	03 Nov.
2009	Daily	09 June	12 June	20 Aug.	18 Sept.	16 Oct.	23 Oct.
	20 kPa	09 June	12 June	28 Aug.	29 Sept.	02 Nov.	09 Nov.
	40 kPa	09 June	12 June	02 Sept.	02 Oct.	03 Nov.	09 Nov.
	70 kPa	09 June	12 June	02 Sept.	02 Oct.	03 Nov.	09 Nov.

Table 2. Van Genuchten parameters and saturated hydraulic conductivity of the field experiment soil for DSR

Soil depth (cm)	Van Genuchten parameters				Saturated hydraulic conductivity (cm d^{-1})
	α (cm d^{-1})	l (-)	η (-)	r ($cm^3 cm^{-3}$)	
0-5	0.0445	-5.503	1.275	0.09	3.90
5-15	0.0649	-5.674	1.281	0.08	3.89
15-25	0.0535	-6.657	1.235	0.10	3.71
25-35	0.0369	-5.954	1.216	0.06	1.16
35-55	0.0258	-5.154	1.216	0.12	1.97
55-65	0.0136	-5.079	1.190	0.08	1.15
65-95	0.0130	-5.236	1.184	0.11	3.44
95-125	0.0230	-6.520	1.174	0.09	3.07
125-155	0.0230	-6.000	1.152	0.15	1.07

2.2.2. Scenarios

The performance of DSR under range of irrigation thresholds (CF to 70 kPa) was evaluated, in a similar manner to that of PTR (Sudhir-Yadav et al., 2011c). The performance of DSR and PTR were then compared for the same irrigation thresholds, soil (clay loam), and climate conditions (weather data for 40 rice seasons from 1970-2009 at Ludhiana). The start time (STTIME)/emergence date of DSR and the seed bed nursery was set to the 165^{th} day of the year (DOY), DSR plant density was set to 110 plants m^{-2} with a row spacing of 20 cm, and PTR was transplanted on the 187 DOY at 33 plants m^{-2}, as in the field experiments. For the first 30 DAS, all DSR treatments were irrigated 2 d after the disappearance of ponded water, before commencing the irrigation treatments, with 50 mm applied at each irrigation. In PTR the irrigation treatments commenced 2 weeks after transplanting, with CF for the first 2 weeks after transplanting in all PTR treatments. The CF treatments were topped up to 50 mm water depth whenever the depth declined to 10 mm. The AWD treatments received 50 mm irrigation water whenever the threshold soil tension was reached.

3. Results

3.1 Parameterization and evaluation of ORYZA2000 for DSR

3.1.1 Crop variables

ORYZA2000 performed well in simulating a range of crop parameters for DSR with CF or an irrigation threshold of 20 kPa, but values were greatly overestimated at 40 and 70 kPa (Figs 1-4, Table 3). The overestimation at 40 and 70 kPa was primarily because of overestimation of green leaf biomass and LAI but stem and panicle biomass were also overestimated. ORYZA 2000 also slightly overestimated biomass and LAI of PTR with irrigation thresholds of 40 and 70 kPa, but the deviations were far less (Sudhir-Yadav et al. 2011c).

As for PTR, performance of ORYZA2000 was good for DSR with CF and 20 kPa, with the slope (β) close to 1 (0.88-1.20) and a relatively small intercept. However, for 40 and 70

Fig. 1. Simulated (lines) and measured dry biomass of the whole crop (♦), leaves (×), stems (●), and panicles (Δ), and of leaf area index (LAI) (o) in different irrigation treatments of DSR in 2008.

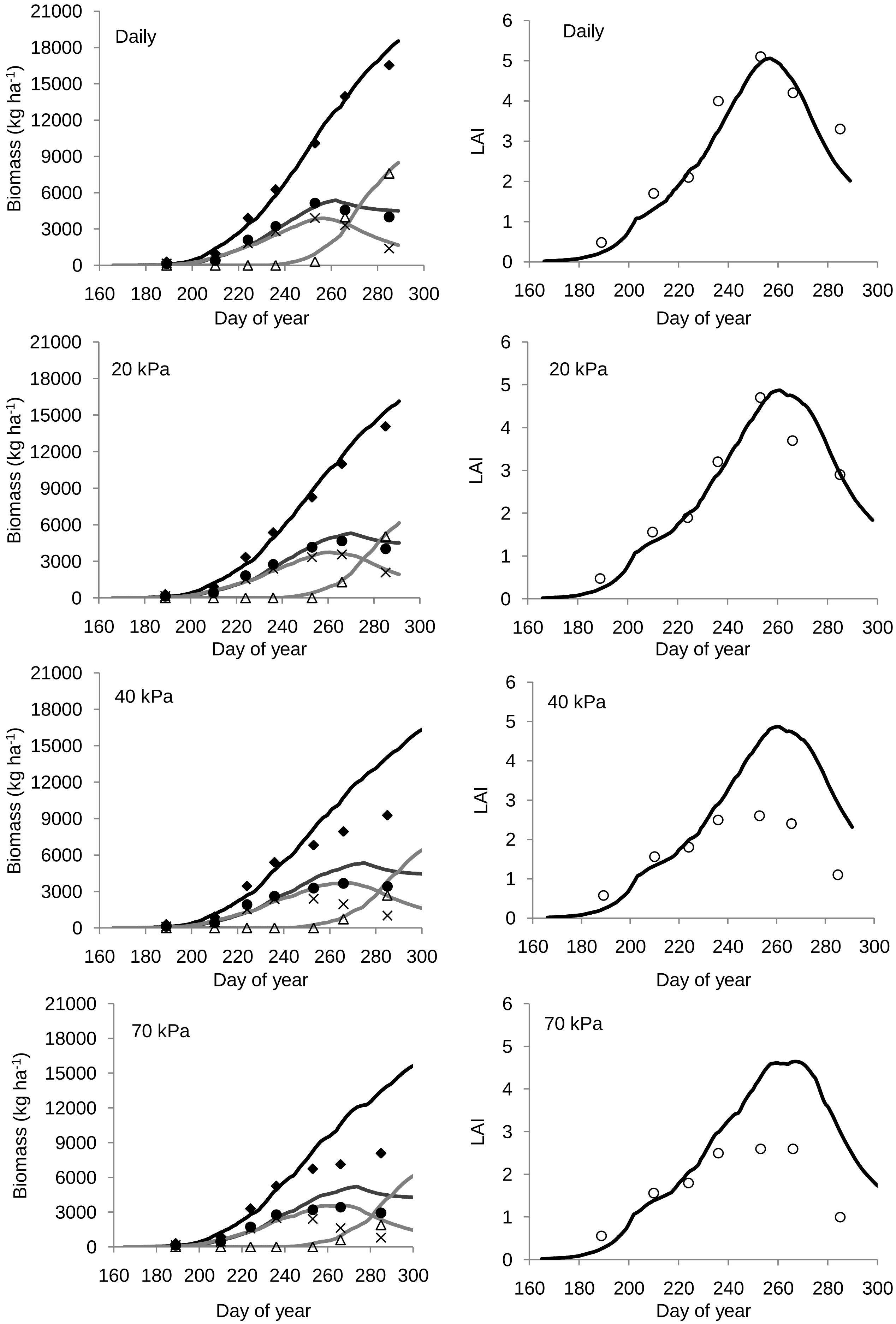


Fig. 2. Simulated (lines) and measured dry biomass of the whole crop (♦), leaves (×), stems (•), and panicles (Δ), and of LAI (o) in different irrigation treatments of DSR in 2009.

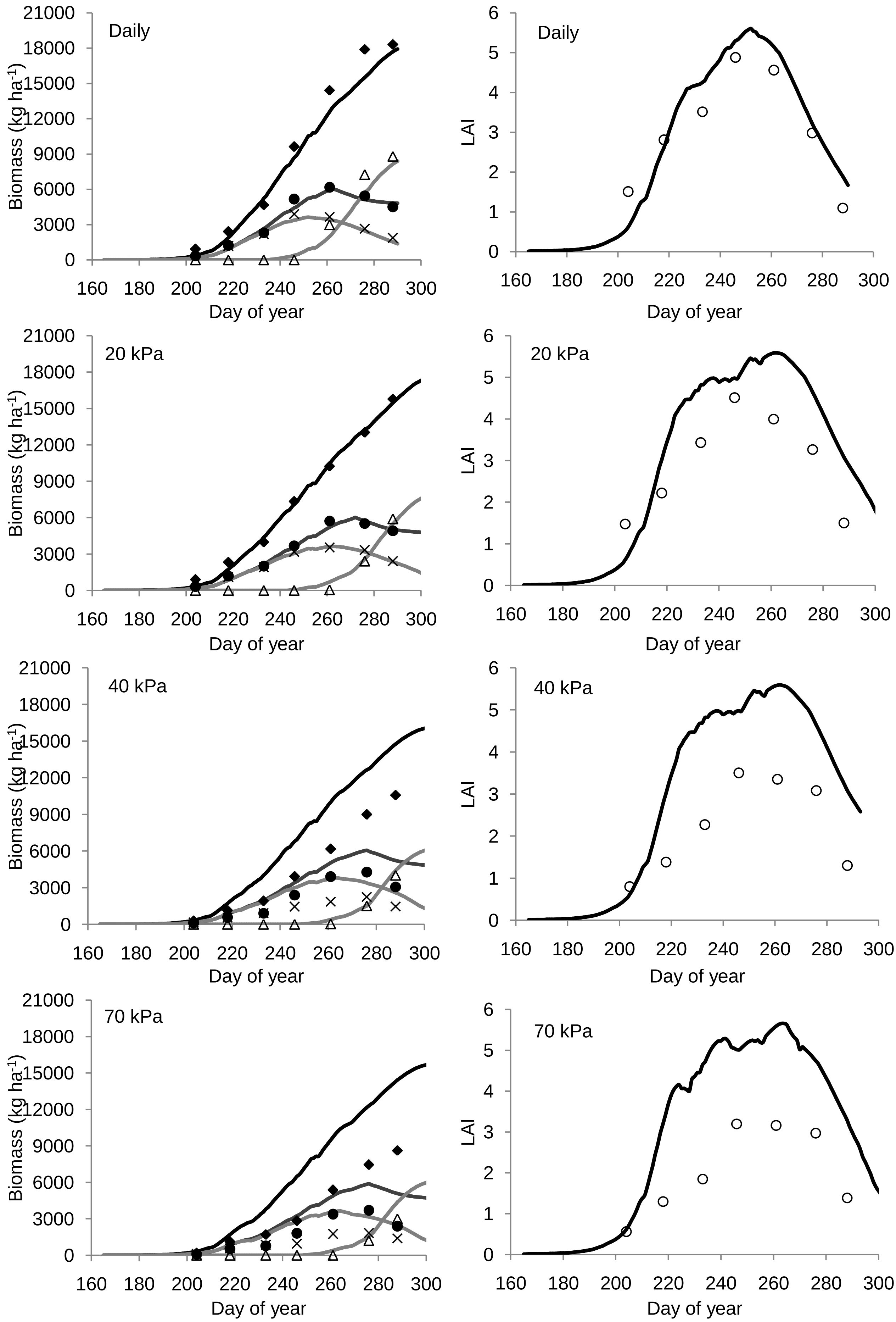


Table 3 Quantitative goodness-of-fit parameters for ORYZA2000 simulation of crop growth variables for DSR over the growing season for different irrigation regimes pooled over 2 seasons.

Crop Variables	Number	Xmean	Xsd	Ymean	Ysd	α	β	R^2	Pt	RMSEa	RMSEn
Daily irrigated											
Total crop biomass (kg ha^{-1})	14	8590	6660	8180	6460	-67	0.96	0.98	0.13	1000	12
Biomass of panicles (kg ha^{-1})	6	5130	3210	4600	3040	-140	0.92	0.95	0.13	840	16
Biomass of stems (kg ha^{-1})	14	3210	2100	3140	2100	-22	0.99	0.97	0.48	352	11
Biomass of dead leaves (kg ha^{-1})	9	1620	1280	1570	1270	-28	0.98	0.98	0.40	178	11
Biomass of green leaves (kg ha^{-1})	14	2140	1270	2020	1250	-30	0.96	0.96	0.11	287	13
Leaf area index	14	3	1	3	2	0	1.07	0.88	0.85	1	19
20 kPa											
Total crop biomass (kg ha^{-1})	14	6920	5240	6950	5530	-320	1.05	0.99	0.83	522	8
Biomass of panicles (kg ha^{-1})	5	2950	2470	3080	2180	493	0.88	0.99	0.47	354	12
Biomass of stems (kg ha^{-1})	14	2960	1980	2950	2090	-140	1.04	0.98	0.86	319	11
Biomass of dead leaves (kg ha^{-1})	9	1210	1010	1230	1060	-28	1.04	0.99	0.52	102	8
Biomass of green leaves (kg ha^{-1})	14	2120	1200	2070	1270	-160	1.05	0.98	0.31	181	9
Leaf area index	14	3	1	3	2	0	1.20	0.79	0.06	1	33
40 kPa											
Total crop biomass (kg ha^{-1})	14	4790	3590	6570	5190	-160	1.40	0.94	0.00	2570	54
Biomass of panicles (kg ha^{-1})	5	1800	1580	2210	1790	237	1.10	0.95	0.10	572	32
Biomass of stems (kg ha^{-1})	14	2200	1500	2910	2120	-79	1.36	0.91	0.01	1060	48
Biomass of dead leaves (kg ha^{-1})	9	958	799	1150	988	110	1.08	0.76	0.28	493	52
Biomass of green leaves (kg ha^{-1})	14	1330	794	2100	1300	253	1.39	0.71	0.00	1070	80
Leaf area index	14	2	1	3	2	0	1.62	0.70	0.00	2	89
70 kPa											
Total crop biomass (kg ha^{-1})	14	4220	3080	6180	4920	-280	1.53	0.92	0.00	2860	68
Biomass of panicles (kg ha^{-1})	5	1350	1170	2210	1760	286	1.42	0.89	0.07	1090	81
Biomass of stems (kg ha^{-1})	14	1950	1340	2720	1980	12	1.38	0.87	0.01	1130	58
Biomass of dead leaves (kg ha^{-1})	8	1000	887	1190	940	262	0.93	0.76	0.29	471	47
Biomass of green leaves (kg ha^{-1})	14	1220	772	1950	1210	467	1.21	0.60	0.00	1050	86
Leaf area index	14	2	1	3	2	0	1.49	0.72	0.00	2	78

Abbreviations are: N= number of data pairs; Xmean=mean of measured values in whole population; Xsd=mean of simulated values in whole population; Ymean= mean of simulated values in whole population; Ysd=standard deviation of simulated values; α=slope of linear relation between simulated and measured value; β= intercept of linear relation between simulated and measured values; R^2=adjusted linear correlations coefficient between simulated and measured values; P(t)= significance of paired t-test; RMSEa=absolute root mean square error; RMSEn=normalized root mean square error (%).

Table 4 Quantitative goodness-of-fit parameters for ORYZA2000 simulation of soil water tension and water loss components in DSR pooled over two growing seasons

Variables	Number	Xmean	Xsd	Ymean	Ysd	α	β	Rsq	Pt	RMSE	RMSEn
Water loss components											
Evapotranspiration	8	696	211	643	119	576	0.10	0.17	0.52	76	31
Drainage	8	876	755	893	822	-40	1.07	0.98	0.79	59	19
Runoff	8	176	177	158	279	-99	1.46	0.93	0.72	44	71
Soil water tension											
20 kPa	186	12	12	8	8	6	0.19	0.07	0.00	13	104
40 kPa	185	18	19	12	14	6	0.33	0.20	0.00	19	104
70 kPa	189	17	19	13	15	7	0.33	0.19	0.00	19	111

Abbreviations are: N= number of data pairs; Xmean=mean of measured values in whole population; Xsd=mean of simulated values in whole population; Ymean= mean of simulated values in whole population; Ysd=standard deviation of simulated values; α=slope of linear relation between simulated and measured value; β= intercept of linear relation between simulated and measured values; R^2=adjusted linear correlations coefficient between simulated and measured values; P(t)= significance of paired t-test; RMSEa=absolute root mean square error; RMSEn=normalized root mean square error (%).

kPa, β was always greater than 1 (1.10-1.60) except for biomass of dead leaves (0.93) at 70 kPa. The range of regression coefficients (R^2) for all growth variables was wider in DSR (0.60-0.99) than PTR (0.88-0.99; Sudhir-Yadav et al. 2011c). For DSR, the R^2 was generally more than 0.95 for CF and 20 kPa, but decreased to 0.70-0.95 for the 40 and 70 kPa treatments. The scatter plots of measured versus simulated total biomass (Fig. 3a) and panicle biomass (Fig. 3b) throughout each season show that the simulated values for DSR were within the magnitude of variation in the measurement, and generally close to the 1:1 line for CF and 20 kPa, while they were overestimated for 40 and 70 kPa for DSR, but not for PTR (Sudhir-Yadav et al. 2011c). The RMSEa for measured and simulated grain yield of DSR was higher than of PTR (0.1-0.3 tha^{-1}). The RMSEa of DSR was 0.09-0.70 t ha^{-1} with RMSEn of 2-14% for CF and 20 kPa and increased to 1.3 and 1.9 t ha^{-1} for 40 and 70 kPa treatments, respectively.

3.1.2 Soil water and water balance components

The was generally good agreement between the simulated and measured values of the water balance components for DSR (Fig. 5, Table 4) and PTR (Sudhir-Yadav et al. 2011c). Each year the model greatly overestimated runoff and underestimated ET in the CF treatment, as in PTR in 2009 (Sudhir-Yadav et al., 2011c). The dynamics of soil water tension at 20 cm depth in both DSR and PTR were generally simulated well each year in all treatments (Fig. 6, Sudhir-Yadav et al., 2011c). The deviation of estimated values of SWT from measured values was higher in DSR (RMSEn = 104-11%) than PTR (RMSEn = 69-99%). The variation was more with 20 and 40 kPa thresholds than the 70 kPa irrigation threshold.

Fig. 3. Simulated vs. measured crop biomass (a) and panicle biomass (b) during the whole crop season for DSR with daily (♦), 20 kPa (●), 40 kPa (Δ) and 70 kPa (□) irrigation thresholds in all years. The solid line is the 1:1 relationship; the dotted lines are plus and minus the measured standard error around the 1:1 line.

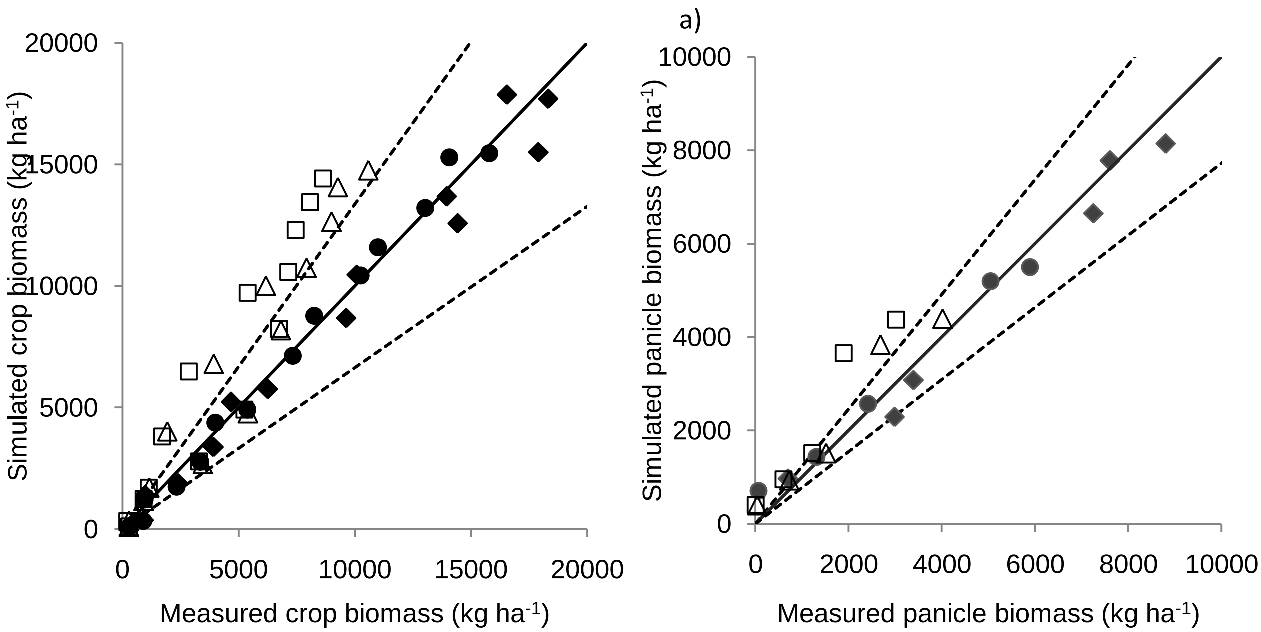


Fig. 4. Measured (black column) and simulated (gray coulmn) grain yield (kg ha^{-1}) of DSR as affected by irrigation schedule in 2008 (a) and 2009 (b). Vertical bars indicate standard error of measured values.

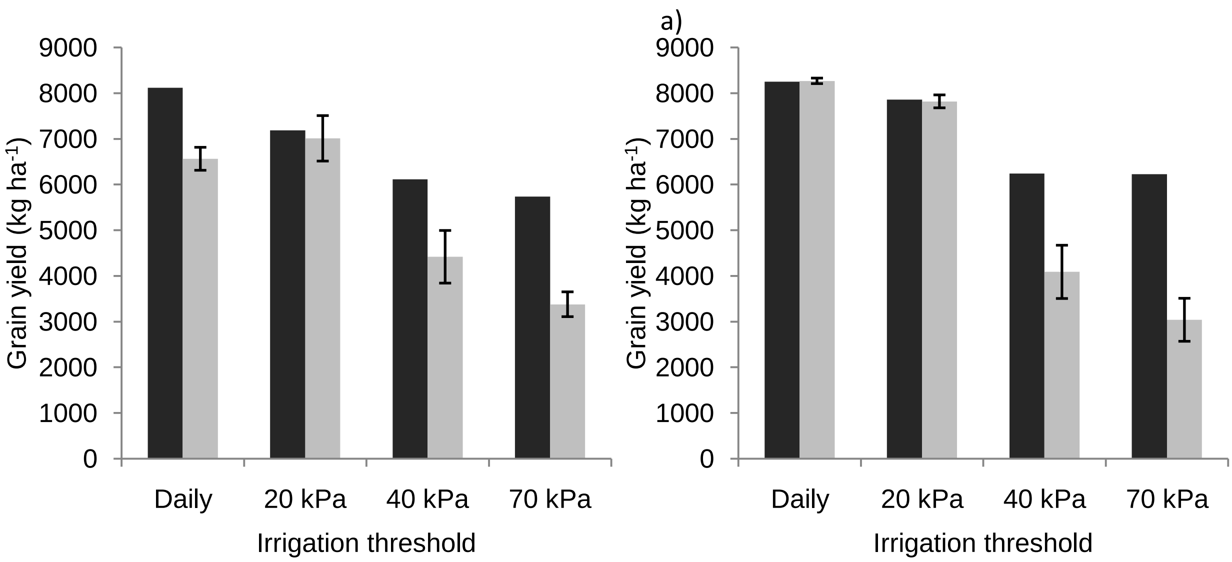
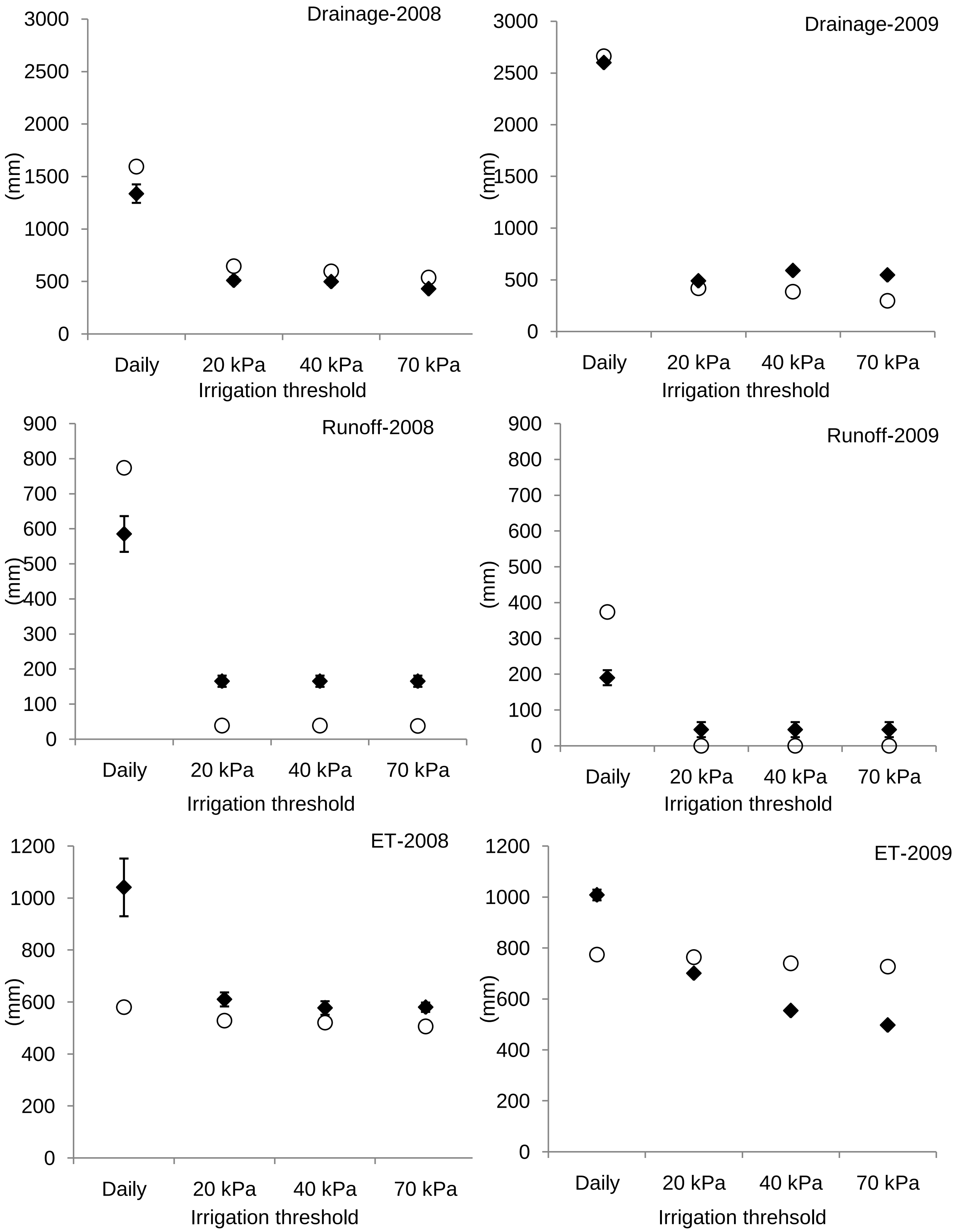


Fig. 5. Simulated (○) and measured (▲) water balance components (mm) of DSR as affected by irrigation threshold in 2008 and 2009. Vertical bars indicate standard error of measured values.



3.2 Simulation analysis

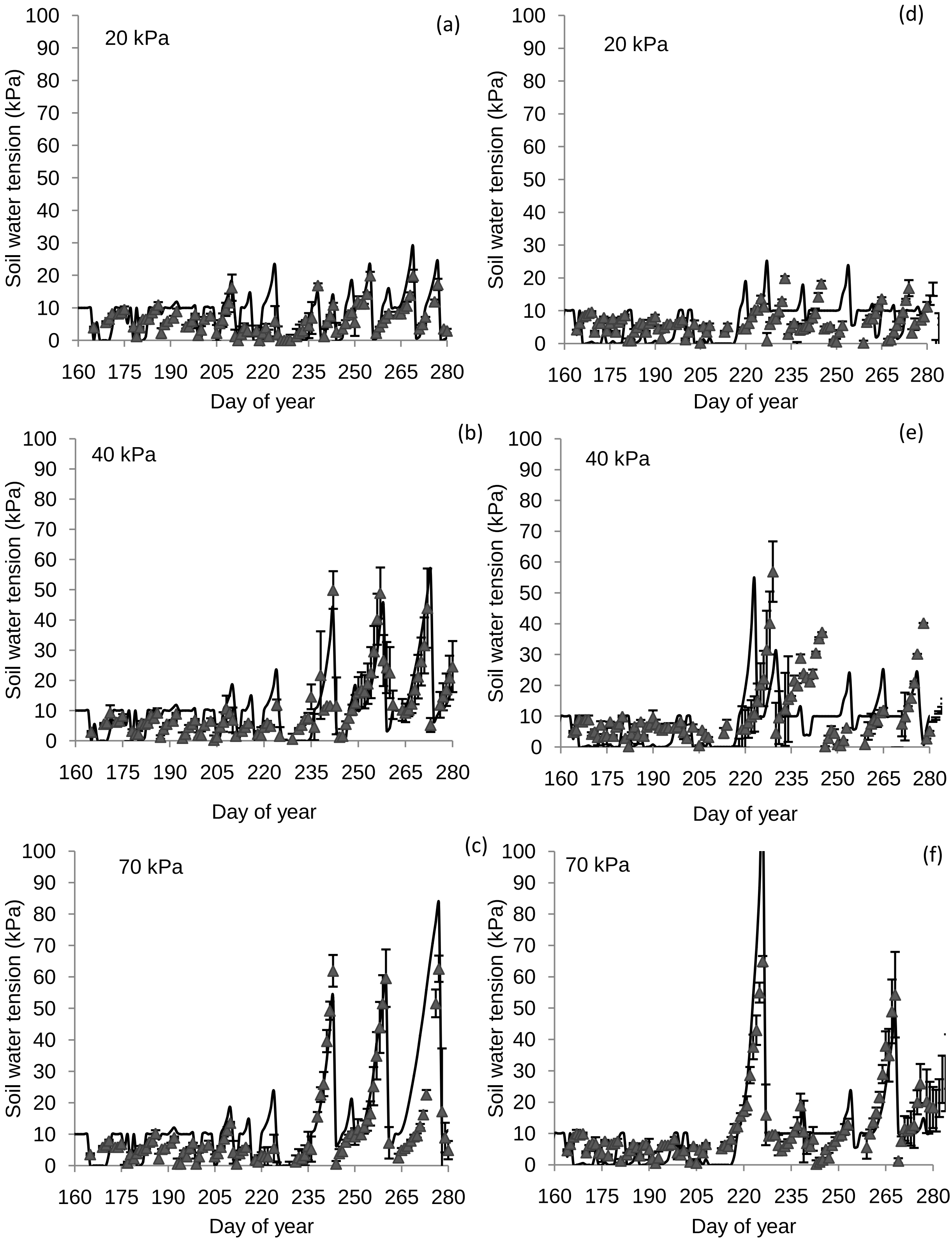
The grain yield response of DSR and PTR to irrigation threshold was very similar (Fig. 7a), although with a consistent trend for slightly higher yield with DSR, more so with frequent irrigation. Average yield of DSR with CF was 9.7 t ha^{-1}, compared with 9.4 t ha^{-1} for PTR. There was a fairly steady decline in yield to 7.2 t ha^{-1} as the irrigation threshold increased from 0 (daily) to 70 kPa.

Irrigation input declined greatly (by 59 and 65%) when changing from daily irrigation to 10 kPa threshold in both DSR and PTR, respectively (Fig. 7a). The irrigation water input was slightly higher in DSR than PTR with daily or 10 kPa scheduling. However, with higher irrigation thresholds, irrigation water input to DSR was lower than to PTR, and gradually declined from 82 % of the input to PTR at 20 kPa to 75% of the input to PTR at 70 kPa.

Of the total water input to both PTR and DSR with CF, the majority (81 and 76%, respectively) drained beyond the root zone (0-60 cm), 12 and 14% was transpired, and 6 and 8% was evaporated directly from the ponded water, on average. The rest (2%) was either lost as runoff or retained in the soil profile. The average proportion of ET to the total water input was very slightly (3%) higher in DSR-CF than PTR-CF. Under AWD, the average proportion of ET to total water input was similar at 10 kPa but was 8-9% higher in DSR with irrigation thresholds ≥20 kPa.

Evapotranspiration of DSR-CF ranged from 590-981 mm with a mean of 705 mm, compared with 481-816 mm (mean 579 mm) for PTR with CF (Fig 7b). In both DSR and PTR, there was a relatively small decline (mean 73 and 60 mm, respectively) in ET in switching from CF to AWD with a threshold of 10 kPa, and a very slight decline in ET as the irrigation threshold increased from 10 to 70 kPa. Evapotranspiration was lower in PTR

Fig. 6 Measured (▲) and simulate (solid line) soil water tension at 20 cm depth in 2008 (a,b,c) and 2009 (d,e,f) of DSR as affected by irrigation threshold.



than DSR by 125 mm in the CF treatments, and the difference gradually declined to 68 mm with a 70 kPa threshold.

Average deep drainage was similar in DSR and PTR with daily and 10 kPa irrigation scheduling, but was 34-46% lower in DSR than PTR when irrigation was scheduled at ≥ 20 kPa (Fig. 7b). Deep drainage declined greatly from around 2000 mm to around 800 mm when changing from CF to 10 kPa scheduling with both PTR and DSR (Fig. 7b). For irrigation thresholds ≥20 kPa, drainage was lower in DSR than PTR, reflecting the lower irrigation input to DSR. Average runoff was small in all DSR (28-53mm) and PTR treatments (28-42 mm)(data not presented), but with high values up to ~300 mm in years when total seasonal rainfall was more than double the long term average (500 mm).

Irrigation water productivity was similar in PTR and DSR with CF, with a mean of 0.37 g kg^{-1} (Fig. 7a).WP_I increased sharply to around 0.9 g kg^{-1} in both DSR and PTR as SWT increased to 10 kPa. At irrigation thresholds ≥20 kPa, WP_I was almost constant both in PTR and DSR, but with much higher values in DSR (1.5-1.7 g kg^{-1}) than PTR (1.2-1.3 g kg^{-1}). The trend in WP_{I+R} was similar to that of $WP_{I,}$ although less pronounced, and with only slightly higher mean values in DSR than PTR at thresholds ≥20 kPa (Fig. 7b). WP_{ET} was lower in DSR than PTR under all irrigation thresholds, by 17% with continuous flooding and the margin decreased to 11% when irrigation was scheduled at 70 kPa. The lower WP_{ET} with DSR was due to higher ET. For both PTR and DSR, WP_{ET} was maximised with irrigation thresholds of 10-20 kPa, and gradually declined at higher thresholds.

4. Discussion

4.1. Model performance

Fig.7 Simulation results over 40 years for comparison of PTR and DSR for grain yield (GY), irrigation water (IR), drainage (D) and evapotranspiration (ET) under different irrigation thresholds.

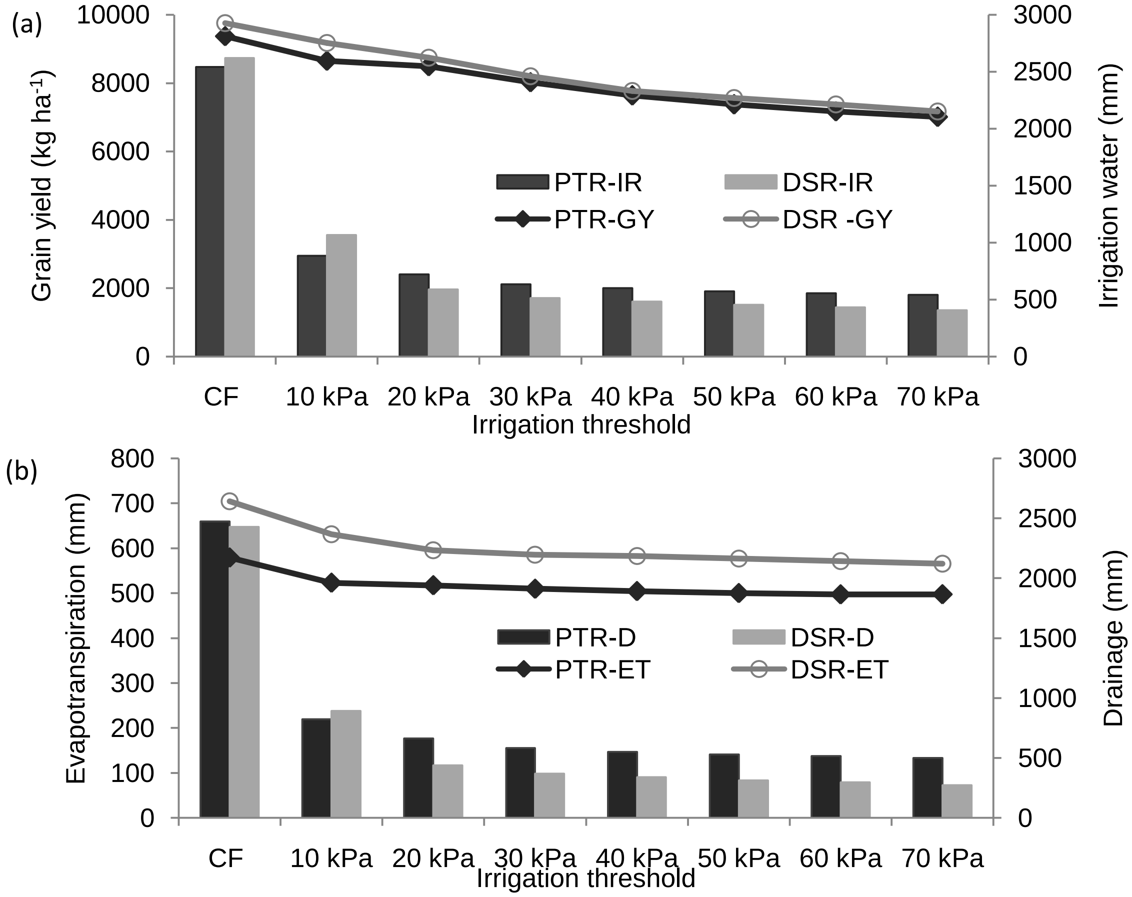
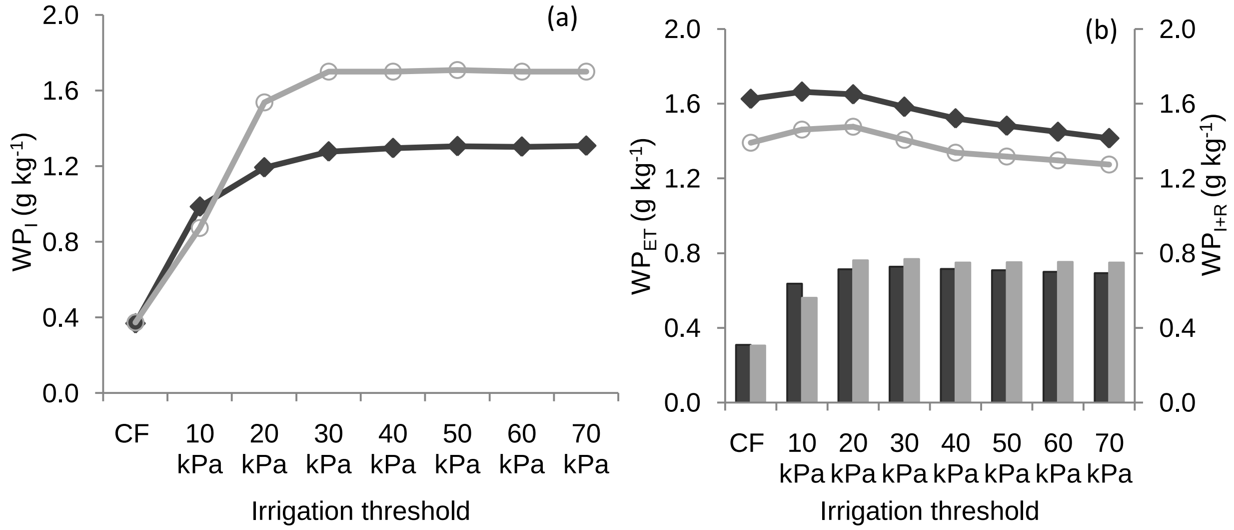


Fig.8 Simulation results over 40 years for comparison of PTR (—◆—) and DSR (⋯○⋯) for (a) irrigation water productivity (WP_I) and (b) water productivity based on evaportranspiration (WP_{ET}) and total input water productivity (WP_{I+R}) (PTR-black column and DSR in grey column).



4.1.1. Calibration and evaluation of ORYZA2000 for DSR

Performance of the calibrated model against a range of crop growth, yield, water and soil water parameters was generally very good for CF and an irrigation threshold of 20 kPa soil water tension during an average and a wetter than average season. The over prediction of simulated and measured grain yield in 2008 in the daily irrigation treatment might be because of crop lodging, which occurred in this treatment about 1 week prior to maturity (Sudhir-Yadav et al., 2011a). The model performed poorly in estimating growth and yield of DSR with thresholds of 40 and 70 kPa each year. The discrepancy was greater in 2009, when the 40 and 70 kPa exhibited strong visual symptoms of Fe deficiency which were not controlled by repeated Fe sprays (Sudhir-Yadav et al., 2011a). The PTR at these thresholds did not exhibit Fe deficiency, and the deviation between simulated and observed values was much lower. Iron deficiency in DSR with AWD has also been reported by other workers in the region and elsewhere (Hobbs et al., 2002; Yadvinder et al., 2008; Kreye et al., 2009). It may be present even before the symptoms are visible (Nayyar et al., 1990). Therefore we suggest that over prediction of crop growth and yield of DSR by the model was at least partly due to Fe deficiency. In the current version of ORYZA (v2.13), there is no module to induce micro-nutrient deficiency along with water deficit stress. The results of the model simulations for irrigation thresholds greater than 20 kPa cannot be applied to situations where Fe deficiency is a problem, which may be the case on significant areas in north west India. However, there are also significant areas where the groundwater is rich in iron, and the results of the model simulations are relevant to such areas.

4.1.2. Simulations – model performance

There are no simulation studies for DSR in north-west India with which to compare our findings. However, similar studies of irrigation threshold were conducted by Bouman et al. (2007) and Xue et al. (2008) in two different environments in China. Both these simulation studies were with aerobic rice (HD297) whose yield potential is almost half that of PAU201. Secondly, none of these studies compared PTR and DSR under similar conditions (with the same cultivar and groundwater depth). As in our study, Bouman et al. (2007) also found a slight decline in the grain yield of aerobic rice as irrigation threshold increased from 10 to 30 kPa in deep ground water table (190 cm) conditions, however, they observed no decline in yield of PTR with irrigation intervals of up to 30 d irrigation schedule under shallow groundwater table (30 cm) conditions.

The slightly higher simulated grain yield of DSR than PTR with frequent irrigation might be associated with its higher plant density (Tekrony and Egli, 1991) and/or avoidance of transplanting shock (Ros et al., 2003). Simulations of PTR using the same plant density as DSR (110 plants m^{-2}), reduced the gap between yield of DSR and PTR from 3.9% (33 hills m-2) (data not presented) to 1.5%. There was a gradual decline in average rice yield with both DSR and PTR as the irrigation threshold increased, and sensitivity to water deficit was similar for both. The simulated yield response to irrigation threshold is generally consistent with the findings of many field experiments (Bouman and Tuong, 2001; Castillo et al., 2006; Venuprasad et al., 2007; de Vries et al., 2010; Sudhir-Yadav et al., 2011a).

With the current options in ORYZA, emergence of the rice crop occurs on the same day as the model run (STTIME) is started and there is no switch to include pre-tillage and pre-sowing irrigations in the total water balance. Therefore, the model is likely to underestimate irrigation input, and overestimate irrigation and input water productivity.

Shifting from CF to AWD reduced irrigation water input by 59-84% in DSR, and by 65-78% in PTR. Under AWD (≥ 20kPa), the irrigation water saving was higher in DSR than PTR. There are generally two phases of higher water input with DSR, as demonstrated for PTR-20 kPa in Figure 8. In ‘Phase-A’, it is due to the high water input (150mm) required for puddling and the recommended practice of continuous flooding in PTR for the first 15 days after transplanting. This phase is the main cause of the higher irrigation input in PTR-20 kPa, with a mean of 478 mm supplied to PTR compared with 260 mm supplied to DSR at the time AWD commences in both DSR and PTR (the start of Phase B). In 'Phase-B', the soil dries faster in PTR compared to DSR which is indicated by the 28% higher slope in PTR than DSR (β=3.24). During this phase, irrigation input is 104 mm lower in DSR than PTR. In field studies, Sudhir-Yadav et al. (2001b) also reported faster drying of soil in PTR than DSR under AWD which was associated with greater cracking in PTR.

The higher ET in DSR than PTR is primarily because DSR is exposed to higher evaporative demand for a much longer period (by 27 days) in the main field, at a time when evaporative demand is very high. Out of the total ET in DSR-CF, 95-139 mm (14-19%) occurred prior to transplanting of the PTR (27 DAS) (Fig. 9). For both establishment methods, there was an average decline in total ET of around 60-70 mm in going from CF to an irrigation threshold of 10 kPa, and for DSR there was a further decline (36 mm) going to a 20 kPa threshold. The decline in ET was associated with a 7% decline in total biomass with 10 kPa in comparison with CF. Total ET was almost constant over irrigation thresholds from 20 to 70 kPa for both establishment methods. Similar trends for the effect of irrigation threshold on ET were also found in simulation studies for locations in China (Bouman et al., 2007; Xue et al., 2008).

4.2 Tradeoffs between establishment method and irrigation management

There were tradeoffs between yield, irrigation amount and various measures of WP with alteration of establishment method or irrigation schedule (Table 5). In both PTR and DSR yield was maximum with CF, with slightly higher yield for DSR. However, measures of water productivity (WP_I, WP_{I+R} and WP_{ET}) were maximum under AWD. Maximum WP_I and WP_{I+R} in both PTR and DSR was achieved when irrigation was scheduled at ≥30 kPa SWT, but maximum WP_I was much (27%) higher for DSR (1.7 g kg^{-1}) than PTR (1.3 g kg^{-}

[1]. However, WP_{ET} of both DSR and PTR was maximum at a lower irrigation threshold (10-20 kPa), and higher for PTR (1.7 g kg^{-1}) than DSR (1.5 g kg^{-1}).

Fig.8 Simulation results over 40 years for comparison of cumulative irrigation inputs in PTR and DSR with a 20 kPa irrigation threshold.

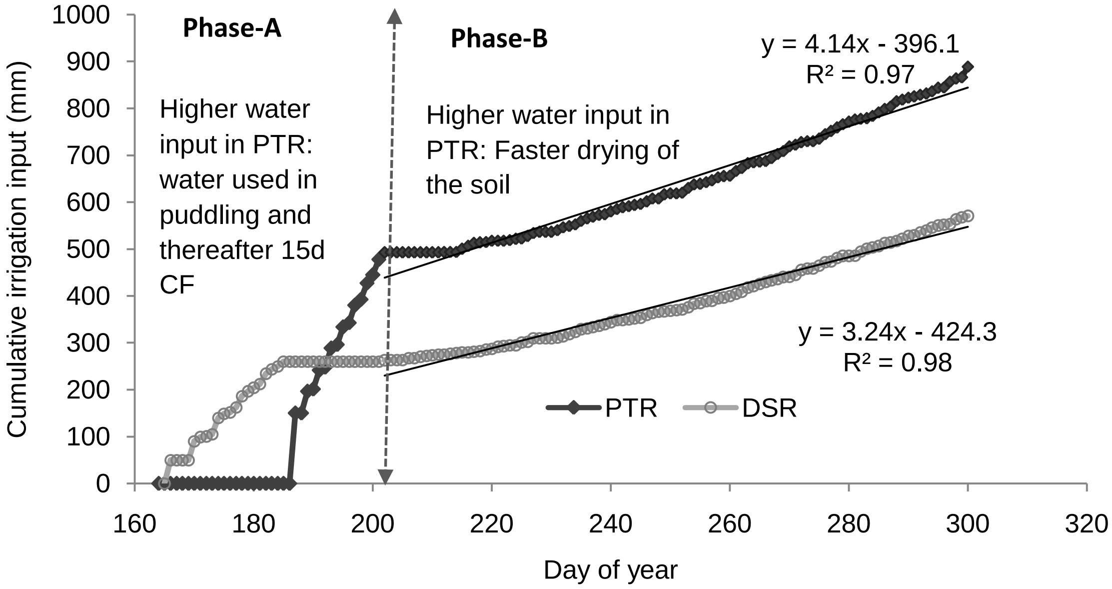


Fig.9 Simulation results over 40 years for comparison of cumulative evapotranspiration (ET) PTR and DSR in continuously flooded treatment.

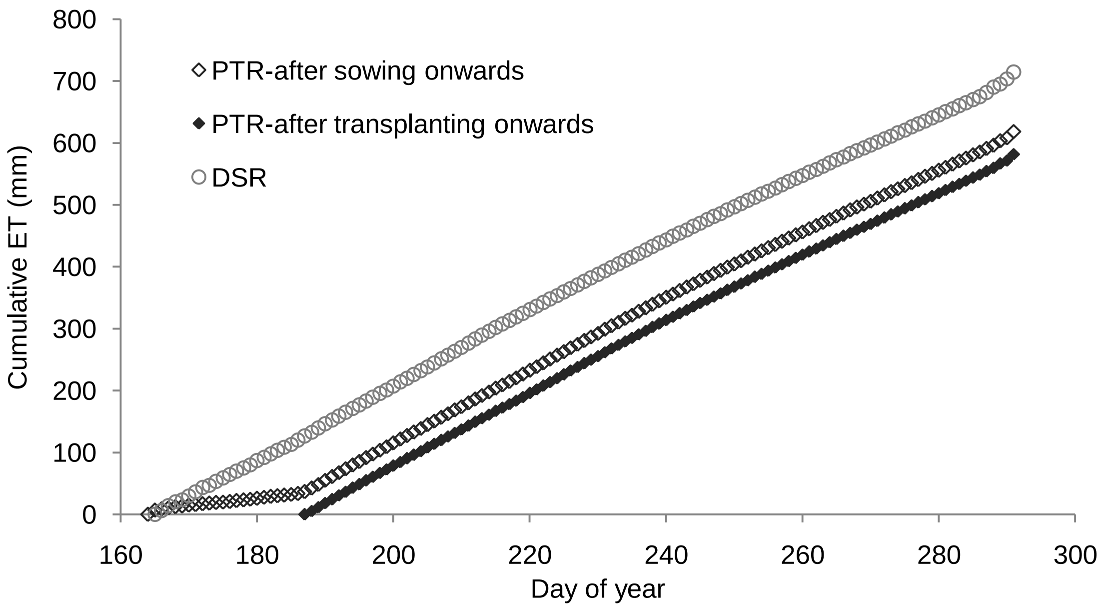


Table 5. Analysis of tradeoffs between yield, water productivity and water depletion for establishment method x irrigation scheduling combinations.

Target	Technology	Predicted outcome			
		Yield ($t\ ha^{-1}$)	WP_I ($g\ kg^{-1}$)	WP_{ET} ($g\ kg^{-1}$)	ET mm
Maximizing yield	DSR-CF	**9.8**	0.37	1.39	705
Maximizing WP_I	DSR-30 kPa	8.2	**1.81**	1.41	586
Maximizing WP_{ET}	PTR-20 kPa	8.5	1.19	**1.66**	518
Minimizing ET	PTR-60 kPa	7.2	1.30	1.45	**497**

Therefore, for a farmer who wants to maximise yield, the modelling results suggest that growing DSR with continuous flooding once the crop is established is the best option. For a farmer for whom irrigation water is limiting, the objective will be to maximise WP_I of his fields, meaning that DSR with an irrigation threshold of 30kPa would be the best option, despite a 16 % yield reduction in comparison with DSR-CF. For a water resource manager, the objective will be to maximise WP with respect to water depletion from a higher spatial scale such as a sub-catchment or catchment. This normally means maximizing WP_{ET}, and the simulation results suggest that PTR-20kPa would be the best option. Finally, if water depletion (ET) is to be minimised while still growing rice, the simulation results suggest that this will be achieved with PTR with AWD; as there is only a very small reduction in ET in increasing the threshold from 10 to 70 kPa (26 mm), and a much larger decline in yield, this suggests that PTR-10 kPa would be the optimum management. .

5. Conclusions

The study shows that under conditions of no or mild water stress (up to 20 kPa SWT) ORYZA2000 performs well in simulating the effects of irrigation schedule on crop growth, yield, water balance components and water productivity of both DSR and PTR in north-west India. However, the model over predicted crop growth and yield at higher irrigation thresholds (40 and 70 kPa), more so with DSR. The poorer performance of the model with DSR under water deficit was at least partly due to the fact that these treatments suffered from iron deficiency, which is not simulated by the model. The scenario analysis for 40 rice seasons predicted that yield of DSR was slightly higher than PTR, more so with CF (by about 4%) and an irrigation threshold of 10 kPa. Yield of both PTR and DSR declined gradually, at about the same rate, as the irrigation threshold increased. In both establishment methods, there was a large irrigation water saving when changing from CF to AWD, and only a small rate of decline in irrigation input as the threshold increased from 10 to 70 kPa. Irrigation input was lower (by about 132 mm) in DSR than PTR for AWD irrigation thresholds ≥20 kPa, mainly due to the large amount of water required for puddling and the fact that the PTR was continuously flooded for 2 weeks after transplanting (recommended practice). However ET was about 100 mm higher in DSR than respective irrigation treatments of PTR, due to the longer duration of DSR in the main field. There were tradeoffs between yield, water productivity and water depletion. Maximum yield occurred with DSR-CF, maximum WP_I with DSR with an irrigation threshold of 30 kPa, maximum WP_{ET} with PTR-20 kPa, and minimum ET in PTR with thresholds ≥20 kPa.

References

Ambast, S.K., Tyagi, N.K., Raul, S.K., 2006. Management of declining groundwater in the Trans Indo-Gangetic Plain (India): Some options. Agric. Water Manage. 82, 279-296.

Arora, V.K., 2006. Application of a rice growth and water balance model in an irrigated semi-arid subtropical environment. Agric. Water Manage. 83, 51-57.

Bhushan, L., Ladha, J.K., Gupta, R.K., Singh, S., Tirol-Padre, A., Saharawat, Y., Gathala, M., Pathak, H., 2007. Saving of water and labor in a rice-wheat system with no-tillage and direct seeding technologies. Agron. J. 99, 1288-1296.

Bouman, B.A.M., Feng, L.P., Tuong, T.P., Lu, G.A., Wang, H.Q., Feng, Y.H., 2007. Exploring options to grow rice using less water in northern China using a modelling approach - II. Quantifying yield, water balance components, and water productivity. Agric. Water Manage. 88, 23-33.

Bouman, B.A.M., Tuong, T.P., 2001. Field water management to save water and increase its productivity in irrigated lowland rice. Agric. Water Manage. 49, 11-30.

Bouman, B.A.M., Wopereis, M.C.S., Kropff, M.J., Tenberge, H.F.M., Tuong, T.P., 1994. Water-use efficiency of flooded rice fields. 2. Percolation and Seepage losses. Agric. Water Manage. 26, 291-304.

Castillo, E.G., Tuong, T.P., Singh, U., Inubushi, K., Padilla, J., 2006. Drought response of dry-seeded rice to water stress timing and N-fertilizer rates and sources. Soil Sci. Plant Nut. 52, 496-508.

Chahal, G.B.S., Sood, A., Jalota, S.K., Choudhury, B.U., Sharma, P.K., 2007. Yield, evapotranspiration and water productivity of rice (*Oryza sativa* L.)-wheat (*Triticum aestivum* L.) system in Punjab (India) as influenced by transplanting date of rice and weather parameters. Agric. Water Manage. 88, 14-22.

Choudhury, B.U., Bouman, B.A.M., Singh, A.K., 2007. Yield and water productivity of rice-wheat on raised beds at New Delhi, India. Field Crops Res. 100, 229-239.

de Vries, M.E., Rodenburg, J., Bado, B.V., Sow, A., Leffelaar, P.A., Giller, K.E., 2010. Rice production with less irrigation water is possible in a Sahelian environment. Field Crops Res. 116, 154-164.

Gill, M.S., 2008. Productivity of direct-seeded rice (*Oryza sativa*) under varying seed rates, weed control and irrigation levels. Indian J. Agric. Sci. 78, 766-770.

Gupta, R.K., Naresh, R.K., Hobbs, P.R., Zheng, J., Ladha, J.K., 2003. Sustainability of post-green revolution agriculture: the rice-wheat cropping systems of the Indo-Gangetic Plains and China. ASAInc, CSSAInc, SSSAInc., Madison, USA.

Hira, G.S., 2009. Water management in northern states and the food security of India. J. of Crop Improv. 23, 136-157.

Hira, G.S., Jalota, S.K., Arora, V.K., 2004. Efficient management of water resources for sustainable cropping in Punjab., Research Bulletin. Department of Soil, Punjab Agriucultural University, Ludhiana, Punjab, p. 20.

Hira, G.S., Khera, K.L., 2000. Water resource management in Punjab under rice–wheat production system. Research Bulletin. Department of Soil, Punjab Agricultural University, Ludhiana, Punjab, India.

Hobbs, P.R., Singh, Y., Giri, G.S., Lauren, J.G., Duxbury, J.M., 2002. Direct-seeding and reduced-tillage options in the rice–wheat systems of the Indo-Gangetic Plains of south Asia. In: Pandey, S., Mortimer, M., Wade, L., Tuong, T.P., Lopez, K., Hardy, B. (Eds.), Proceedings of the Direct Seeding: Research Issues and Opportunities, IRRI, Los Baños/Phillipines/Bangkok, pp. 201-215.

Jalota, S.K., Singh, K.B., Chahal, G.B.S., Gupta, R.K., Chakraborty, S., Sood, A., Ray, S.S., Panigrahy, S., 2009. Integrated effect of transplanting date, cultivar and irrigation on yield, water saving and water productivity of rice (*Oryza sativa* L.) in Indian Punjab: Field and simulation study. Agric. Water Manage. 96, 1096-1104.

Khade, V.N., Patil, B.D., Khanvilkar, S.A., Chavan, L.S., 1993. Effect of seeding rates and level of N on yield of direct-seeded (Rahu) summer rice in Konkan. J. Maharastra Agric. Uni. 18, 32-35.

Kreye, C., Bouman, B.A.M., Castaneda, A.R., Lampayan, R.M., Faronilo, J.E., Lactaoen, A.T., Fernandez, L., 2009. Possible causes of yield failure in tropical aerobic rice. Field Crops Res. 111, 197-206.

Kukal, S.S., Aggarwal, G.C., 2002. Percolation losses of water in relation to puddling intensity and depth in a sandy loam rice (*Oryza sativa*) field. Agric. Water Manage. 57, 49-59.

Ladha, J.K., Pathak, H., Tirol-Padre, A., Dawe, D., Gupta, R.K., 2003. Productivity trends in intensive rice-wheat cropping systems in Asia. In: Ladha, J.K., Hill, J.E., Duxbury, J.M., Gupta, R.K., Buresh, R.J. (Eds.), Improving the Productivity and Sustainability of Rice-Wheat Systems: Issues and Impacts. ASAInc, CSSAInc, SSSAInc, Madison, USA, pp. 45-76.

Nayyar, V.K., Takkar, T.N., Bansal, R.L., Singh, S.P. Kaur, Narinder P., Sadana, U.S., 1990. Micronutrients in soils and crops of Punjab. Research Bulletin. Department of Soils, Punjab Agricultural University, Ludhiana, Punjab.

Qureshi, A.S., Masih, I., Turral, H., 2004. Comparing land and water productivities of transplanted and direct dry seeded rice for Pakistani Punjab. J. Applied Irrig. Sci. 41, 47-60.

Ros, C., Bell, R.W., White, P.F., 2003. Seedling vigour and the early growth of transplanted rice (*Oryza sativa*). Plant and Soil 252, 325-337.

Saharawat, Y.S., Gathala, M., Ladha, J.K., Malik, R.K., Singh, S., Jat, M.L., Gupta, R.K., Pathak, H., Singh, K., 2009. Evaluation and promotion of integrated crop and resource management in the rice-wheat system in north-west India. In: Ladha, J.K., Yadvinder-Singh, Erenstein, O., Hardy, B. (Eds.), Integrated crop and resource management in the rice-wheat system of South Asia. Los Baños (Philippines): International Rice Research Institute, pp. 133-150.

Saharawat, Y.S., Singh, B., Malik, R.K., Ladha, J.K., Gathala, M., Jat, M.L., Kumar, V., 2010. Evaluation of alternative tillage and crop establishment methods in a rice-wheat rotation in North Western IGP. Field Crops Res. 116, 260-267.

Sharma, P., Tripathi, R.P., Singh, S., 2005. Tillage effects on soil physical properties and performance of rice-wheat-cropping system under shallow water table conditions of Tarai, Northern India. Eu. J. Agron. 23, 327-335.

Singh, V.P., Singh, G., Singh, S.P., Kumar, A., Singh, Y., Johnson, D.E., 2008. Direct seeding and weed management in the irrigated rice-wheat production system. In: Singh, Y., Singh, V.P., Chauhan, B., Orr, A., Mortimer, A.M., Johnson, D.E., Hardy, B. (Eds.), Direct seeding and weed management in the irrigated rice-wheat cropping system of the Indo-Gangetic Plains. Los Baños (Philippines): International Rice Research Institute and Pantnagar (India):Directorate of Experiment Station, G.B. Pant University of Agriculture and Technology, pp. 131-138.

Sudhir-Yadav, Gill, G., Humphreys, E., Kukal, S.S., Walia, U.S., 2011a. Effect of water management on dry seeded and puddled transplanted rice. Part 1: Crop performance. Field Crops Res. 120, 112-122.

Sudhir-Yadav, Humphreys, E., Kukal, S.S., Gill, G., Rangarajan, R., 2011b. Effect of water management on dry seeded and puddled transplanted rice: Part 2: Water balance and water productivity. Field Crops Res. 120, 123-132.

Sudhir-Yadav, Tao Li, Humprheys, E., Gill, G., Kukal, S.S, 2011. Evaluation and application of ORYZA2000 for irrigation scheduling of puddled transplanted rice in north west India. Field Crops Res. (doi: 10.1016/j.fcr.2011.03.004).

Tekrony, D.M., Egli, D.B., 1991. Relaitonship of seed vigor to crop yield- a review. Crop Sci. 31, 816-822.

Tuong, T.P., 2000. Productive water use in rice production: Opportunities and limitations. J. Crop Prod. 2, 241-264.

Venuprasad, R., Lafitte, H.R., Atlin, G.N., 2007. Response to direct selection for grain yield under drought stress in rice. Crop Sci. 47, 285-293.

Xue, C.Y., Yang, X.G., Bouman, B.A.M., Deng, W., Zhang, Q.P., Yan, W.X., Zhang, T.Y., Rouzi, A., Wang, H.Q., 2008. Optimizing yield, water requirements, and water productivity of aerobic rice for the North China Plain. Irrig. Sci. 26, 459-474.

Yadvinder, S., Brar, N.K., Humphreys, E., Bijay, S., Nayyar, A., Timsina, J., 2008. Yield and N use efficiency of permanent bed rice-wheat systems in north-western India: effect of N fertilisation, mulching and crop establishment method. Permanent beds and rice-residue management for rice-wheat systems in the Indo-Gangetic Plain. Proceedings of a workshop held in Ludhiana, India, 7-9 September 2006., pp. 62-78.

CHAPTER 6

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Since the 1980's, there has been considerable debate about the potential benefits of the replacement of PTR with DSR in north-west India. These benefits are considered to include reduced labour requirement, reduced tillage costs and diesel burning, improved soil properties for crops grown in rotation with rice, and water saving. However, many researchers have identified various management challenges, especially in relation to weeds, macro- and micro- nutrients, soil borne pathogens and water, and yield of DSR has generally been lower than that of PTR. To date, there has been a lot of research on weed management options, but very little on the other challenges. In addition to direct effects on crop performance, water management also strongly affects the incidence of weeds and herbicide efficacy, the availability of macro- and micro- nutrients, and the activity of soil borne pathogens. Furthermore, the question of whether simply changing establishment method really saves water has not been addressed. Therefore, research on water management for DSR in comparison with PTR was urgently needed.

A two-pronged approach was adopted – (i) field experiments to evaluate the effects of irrigation threshold on crop performance, components of the water balance and various measures of water productivity for PTR and DSR, and (ii) use of a parameterised and validated crop model (ORYZA2000) to expand the analysis for the weather conditions over 40 rice seasons. The performance of ORYZA2000 in predicting crop growth and yield was good for a range of irrigation thresholds from continuous flooding up to 20 kPa soil tension for both PTR and DSR, but sub-optimal for some parameters for PTR at higher thresholds, and unsatisfactory for DSR at thresholds >20 kPa. The model also predicted soil water dynamics well, and generally predicted components of the water balance satisfactorily. The effects of increasing irrigation threshold were captured well in the simulations of all crop, soil water and other water parameters. However, the current version of model needs to be calibrated for each G×E×M situation, which greatly diminishes the ability of a calibrated version in one situation to be extrapolated to other stress situations. Also, the model does not produce yield components such as panicle density, which limits the ability to diagnose the causes of different treatment responses.

Yield trends

The model simulations showed a long term decline in potential rice yield over the period 1979-2009, consistent with the results of long-term yield trials. The decline in yield in the simulations was strongly associated with a significant decline in net solar radiation over time, possibly due to increasing air pollution in north-west India. This is a significant finding as in the past yield decline has often been attributed to abiotic and biotic factors other than climate.

Comparison of PTR and DSR as affected by water management

Dry seeded rice is widely perceived to be a “water saving” technology, especially by many agriculturalists in the IGP. However, dry seeding is merely an establishment method. Based on field experiments over two contrasting seasons in Punjab, India (Chapters 2 and 3), and backed up by simulations using ORYZA2000 (Chapters 4 and 5), this thesis shows that whether or not DSR reduces irrigation input relative to PTR depends on water management of both establishment methods. In fact, the thesis shows that irrigation water use can be even higher in DSR and PTR when both crops are continuously flooded.

The field experiments and model simulations showed similar yield of PTR and DSR with daily irrigation. However, crop performance of DSR was slightly better than that of PTR. The model simulations suggested that this was at least partly due to the higher plant density in DSR. Secondly, early growth of PTR was probably reduced by transplanting shock, which is avoided with DSR.

The field experiments and model simulations also showed that yield of both DSR and PTR declined as the irrigation threshold of the alternate wetting and drying (AWD) treatments increased. In the field experiments, crop performance of DSR with a 20 kPa threshold was comparable to that of PTR with CF or with a 20 kPa irrigation threshold. However, at higher thresholds (40 and 70 kPa), DSR growth and yield were lower than of PTR within respective irrigation treatments. The lower yield was associated with reduced tillering and/or higher tiller mortality leading to lower panicle density, and also with fewer florets per panicle and lower floret fertility and grain weight. Thus the DSR at higher irrigation thresholds appeared to be stressed throughout most of the growth season, from at least the tillering stage onwards. The poorer performance of DSR at higher thresholds was at least partly due to iron deficiency in the lower (average) rainfall season. It is likely that in drier than average seasons, the problem of iron deficiency will be even more severe than observed in the average and above average rainfall seasons of this study on a clay loam soil, especially on coarser textured soils. However, there are also significant areas in Punjab where the groundwater is rich in iron where iron deficiency is unlikely to be a problem in DSR with AWD.

The model predicted that additional irrigation at panicle initiation (PI) and/or flowering (FL) slightly reduced the yield penalty with AWD, with higher yield with ponding at these stages than allowing the soil to dry for 2d between irrigations. Continuous flooding for two weeks at FL was more effective in reducing the yield penalty with AWD than CF at PI, but the biggest improvement in yield was with CF at both stages. This additional irrigation reduced the average yield loss from 9 to 5% for AWD at SWT thresholds of 10 and 20 kPa.

There have been many anecdotal claims that the duration of DSR is shorter than that of PTR. However, the field experiments showed that the duration of DSR and PTR was similar with daily irrigation, and that AWD increased duration with both establishment methods, more so in the drier year. The duration of DSR was increased by more than that of PTR with the same AWD irrigation threshold. Maturity of DSR was delayed by 8–17 d with AWD compared to PTR. In 2009, DSR-20 and 40 kPa matured 9 d later than PTR at these irrigation thresholds. The maturity of the AWD treatments was delayed due to delayed panicle initiation (PI) and extended duration between PI and anthesis.

The field and modelling studies showed that, irrespective of crop establishment method, there was large irrigation water saving in all AWD irrigation regimes compared to CF. The magnitude of irrigation water saving in DSR in comparison with PTR depended on irrigation schedule. There was no irrigation water saving in DSR compared to PTR when the crop was irrigated daily, and in fact the irrigation input to DSR-CF was higher than to PTR-CF in the second year (2nd year without puddling in the DSR) of the field experiments. However, the irrigation input to DSR with AWD was lower than to PTR within respective irrigation scheduling treatments. For example, DSR irrigated at 20 kPa SWT reduced the irrigation input by 30-53% in comparison with PTR-20 kPa in the field experiments, and by 18% in the model simulations. The reduced input with DSR was primarily due to the recommended practice of 15 d of continuous flooding after transplanting in PTR, and to only a small degree due to reduced frequency of irrigation in DSR. The reduced frequency of irrigation in DSR with AWD was due to slower soil drying which was associated with less cracking than in PTR.

The irrigation water saving with AWD in comparison with CF in the field experiments was largely due to reduced deep drainage, and to a lesser extent due to lower seepage, runoff and ET. Decline in ET in AWD treatments with higher irrigation thresholds was associated with decline in biomass production, and therefore reduced transpiration as indicated by the model simulations. The irrigation water saving of DSR-20 kPa in comparison with PTR-20 kPa was due to reduced seepage, or a combination of reduced seepage and runoff. Seepage was much higher in all PTR treatments than in DSR in both seasons as a result of ponding the plots for the first 2 weeks after transplanting. Deep drainage in DSR was higher than in PTR in respective irrigation treatments as a result of higher infiltration rate due to lack of puddling. The longer crop duration (by about 1 month) in the main field under DSR also increased the opportunity for deep drainage from both irrigation and rainfall.

All measures of water productivity analysed (WP_I, WP_{I+R} and WP_{ET}) were maximum under AWD in both the field and modelling studies. In the field experiments, all three were maximised with an irrigation threshold of 20 kPa, without loss of yield, for both establishment methods. The model simulations also showed maximum WP_{ET} at a similar threshold (10-20 kPa). However, the model predicted maximum WP_I and WP_{I+R} in both PTR and DSR when irrigation was scheduled at ≥30 kPa SWT because of under prediction of the decline in yield as the irrigation threshold increased.

Conclusions

- It is possible to achieve similar yield of rice established with DSR to that of PTR in north-west India.
- Grain yield of both PTR and DSR was extremely sensitive to irrigation threshold, however the yield decline with DSR was greater than with PTR; this was at least partly due to iron deficiency at irrigation thresholds >20 kPa, despite several iron sulphate sprays.
- An irrigation threshold of 20 kPa was the optimum in terms of maximising grain yield, WP_I, WP_{I+R} and WP_{ET} of both PTR and DSR.
- There were very large reductions in irrigation water input in changing from CF to AWD, primarily due to less drainage.

- Deep drainage in DSR was higher than in PTR
- The ORYZA2000 crop model performed well in predicting the effects of irrigation schedule on crop growth, yield, water balance components and water productivity of PTR and DSR with no or little water deficit in north-west India; the model predictions of crop performance were sub-optimal with irrigation thresholds of 40 and 70 kPa, especially for DSR; the poorer predictions with DSR were at least partly due to iron deficiency, which is not simulated by the model.
- The model always predicted a yield decline with AWD for irrigation thresholds ≥10 kPa, but with higher irrigation water productivity.
- Additional irrigation at PI and/or flowering reduced the loss of yield with AWD, but not completely.

Recommendations

Based on the findings of this thesis, the following areas for further research are recommended:

i. **The performance of DSR as affected by irrigation management needs to be evaluated over a wider range of soil types, seasonal conditions and climates.**

The similar yields of DSR and PTR irrigated daily or at 20 kPa SWT on a clay loam soil at Ludhiana demonstrate the feasibility of DSR with AWD in north-west India. However, these results came from only two rice seasons and a single soil type. Even though the rainfall pattern in the two seasons was very different, the total rainfall was average or above average each year. As a result, the number of drying events in the AWD treatments was limited relative to the situation in drier years. Furthermore, there is considerable interest in promoting DSR across the IGP, including in the very low (often zero) rainfall Boro season in Bangladesh, the low rainfall monsoon season in Punjab Pakistan (average seasonal rainfall of about 400 mm), and the relatively high rainfall monsoon season of the eastern Ganges Plain in India.

ii. **The effect of irrigation threshold during different crop stages needs further investigation.**

In the field experiments, the same irrigation threshold was used throughout the season after establishment. However, it is well established that rice is more sensitive to water deficit at critical stages, specifically around panicle initiation and flowering. The modelling studies suggested that there was a yield benefit from more frequent irrigation during these stages, and this needs to be tested in field studies, together with the possibility of higher thresholds during less sensitive stages.

iii. **Simple, cheap and robust methods are needed to assist farmers to schedule irrigations for safe AWD with DSR.**

The field water tube is a simple, cheap and robust method for applying safe AWD in PTR. It needs to be evaluated for DSR. However, it is likely that in the absence of puddling, especially on coarser textured soils, there will not be a perched water table. Alternative approaches, such as the simple tube tensiometer developed by Punjab Agricultural University, need to be evaluated for DSR, in research experiments and in participatory farmer evaluations.

iv. **Germplasm with greater tolerance to iron deficiency needs to be developed.** Strong iron deficiency symptoms were evident in DSR with irrigation thresholds ≥40 kPa, which were not overcome with repeated iron sulphate sprays. Iron deficiency accounted for at least part of the poorer performance of DSR relative to PTR at these thresholds. Greater tolerance to iron deficiency is needed to avoid the risk of adverse effects on crop performance in the absence of continuous flooding of DSR.

v. **Agroecological zones where iron deficiency is likely to occur with DSR with sub-optimal AWD need to be identified.**

Iron deficiency in rice is more likely to occur on coarser textured soils such as sandy loams in the absence of continuous flooding, and this thesis shows that it can also occur on heavier soils, in this case a clay loam. However there are regions in north-west India where the ground water is rich in iron. The areas where there is a high concentration of iron in the ground water, and/or where the soils are heavier textured (clay) should be identified, and targeted for promotion of DSR with AWD using current varieties.

vi. **Evaluation of the effects of DSR with AWD in comparison with PTR on crop performance and components of the water balance is needed in farmers' fields.**

The irrigation time in small plots (a few minutes) is very small compared with farmers' fields (a few hours), and therefore deep drainage losses with AWD are likely to be less in small plots. Furthermore, seepage is likely to be disproportionately high in small plots because of the much higher perimeter to area ratio in small plots, smaller bunds, and buffer areas outside the bunds.

vii. **The ORYZA2000 model needs to be improved to simulate the effects of water deficit stress on crop phenology and yield components**

The field experiments showed that rice phenology is strongly affected by water deficit. In the current version of ORYZA2000 (V2.13), crop development rates and drought stress sensitivity coefficients are G×E×M parameters, and therefore the model needs to be calibrated against each stress treatment, each season, for accurate simulation. Therefore, model improvements which incorporate development rates and stress coefficients into genetic parameters are highly desirable to enable application of the calibrated model across a wider range of environmental and management conditions. Also, ORYZA2000 does not produce outputs of yield components such as panicle density, which limits its usefulness in diagnosing the causes of different treatment responses.

viii. **The ability of ORYZA2000 to simulate the effects of water deficit at thresholds >20 kPa needs to be improved.**

The ability of ORYZA2000 to simulate crop growth and yield of PTR irrigated at thresholds >20 kPa was sometimes sub-optimal, and was unsatisfactory for DSR. The ability to simulate crop performance at higher levels of water deficit stress is needed for proper evaluation of the effects irrigation threshold on crop performance to help identify optimum irrigation management.

ix. **ORYZA2000 needs to be modified to include pre-tillage and pre-sowing water inputs in the water balance.**

The current version of ORYZA2000 starts the emergence of the rice crop on the same day as the model run (STTIME) is started, and there is no switch to include pre-sowing irrigations for DSR or pre-puddling irrigations for PTR in the total water balance. Therefore total irrigation input is likely to be underestimated.

x. **The impacts of adoption of "water saving" technologies such as PTR and DSR with AWD need to be evaluated at higher spatial scales.**

The field experiments and modelling studies showed that most of the irrigation water saving in switching from CF to AWD, and from PTR with AWD to DSR with AWD, was due to reduced deep drainage, runoff and seepage. The degree to which irrigation water saving will reduce the decline in the ground water table in north-west India (or elsewhere) is not clear, and depends on how much of the deep drainage, runoff and seepage is recycled in the region. Seepage through or under the bunds in farmers' fields will largely be lost as runoff or deep drainage. Deep drainage water flows to the groundwater, from where it is recycled by groundwater pumping in the major rice–wheat areas of north-west India, and is not a loss from the system. Runoff makes its way to surface water bodies (ponds, streams) where it may be reused in various ways. Reducing ET reduces the loss from the surface/groundwater system and will thus help reduce the decline in the groundwater. The field experiments showed a decline of 100-200 mm in ET by changing from PTR-CF to PTR-20 kPa or DSR-20 kPa, while the model simulations showed a smaller reduction of about 60-70 mm. Using the more conservative (lower) estimate, and assuming that all rice in Punjab is currently grown using continuous flooding, converting from CF to AWD would result in a substantial reduction in groundwater depletion due to rice-wheat cropping systems (Humphreys et al., 2010). However, given the adoption of safe AWD (20 kPa threshold), whether there is any benefit in changing establishment method from PTR to DSR is less clear. The field experiments suggest little difference (1-58 mm) in ET from PTR and DSR with the same irrigation threshold, and the modelling studies suggest an increase in ET of 125 mm (10 kPa irrigation threshold) to 68 mm (70 kPa) in changing from PTR to DSR. In comparison, the model simulations of Jalota and Arora (2002) suggest a reduction in ET of 50-70 mm in changing from a rice-wheat cropping system to maize-wheat. Therefore, further field studies, combined with crop modelling studies and spatial hydrological studies, are needed to investigate the impacts of changes in cropping systems and management on groundwater depletion at higher spatial scales, and to identify optimum land use and management.