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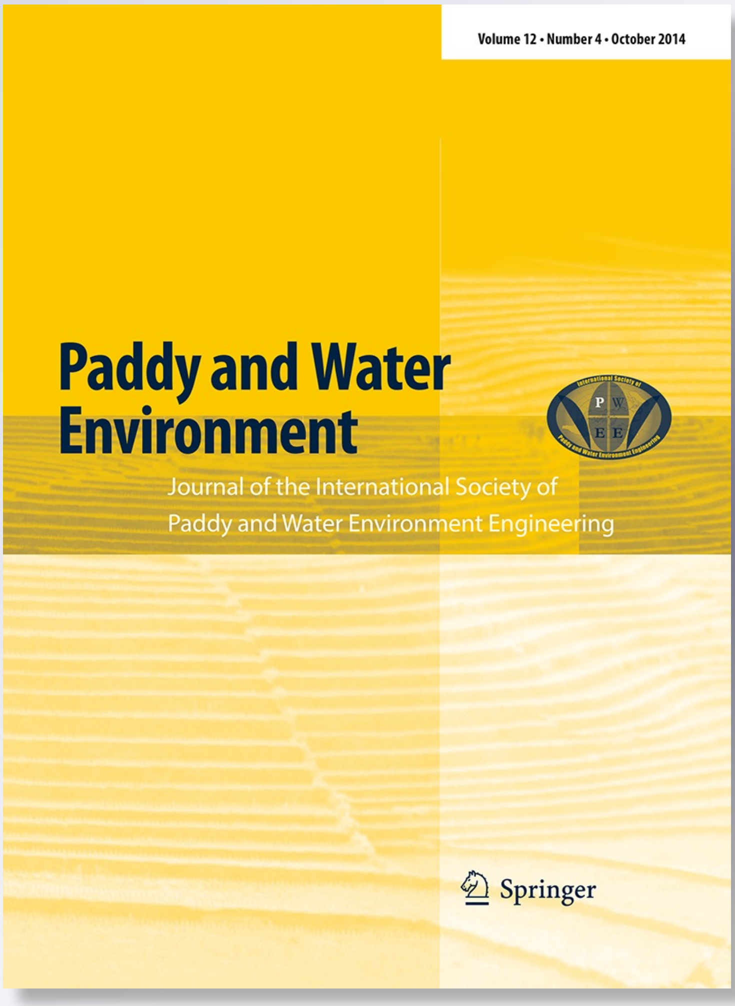

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ARTICLE

Impact of water management on yield and water productivity with system of rice intensification (SRI) and conventional transplanting system in rice

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Abstract The system of rice intensification (SRI) reportedly enhances yield with less water requirement. This claim was investigated to determine the effects of alternative cultivation methods and water regimes on crop growth and physiological performance. Treatment combinations compared SRI with the conventional transplanting system (CTS) using standard practices, evaluating both along a continuum from continuous flooding to water applications at 1, 3, 5, or 7 days after disappearance of ponded water (DAD), subjecting plants to differing degrees of water stress while reducing total water expenditure. SRI methods gave significant changes in plants' phenotype in terms of root growth and tillering, with improved xylem exudation and photosynthetic rates during the grain-filling stage compared to CTS. This resulted in significant increases in panicle length, more grains and more filled grains panicle^{-1}, greater 1,000-grain weight, and higher grain yield under SRI management. Overall, averaged across the five water regimes evaluated, SRI practice produced 49 % higher grain yield with 14 % less water than under CTS; under SRI, water productivity increased by 73 %, from 3.3 to 5.7 kg ha-mm^{-1}. The highest CTS grain yield and water productivity were with the 1-DAD treatment (4.35 t ha^{-1} and 3.73 kg ha-mm^{-1}); SRI grain yield and water productivity were the greatest at 3-DAD (6.35 t ha^{-1} and 6.47 kg ha-mm^{-1}).

Keywords Conventional transplanting system · Irrigation · Rice · System of rice intensification · Water productivity

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Introduction

Rice (*Oryza sativa* L.) is both a major staple food for much of the world's population and the largest consumer of water in the agricultural sector. The standard system for growing irrigated rice around the world is to flood paddy fields and maintain standing water on them. This uses a large amount of water because of high water losses through evaporation, seepage, and percolation. As water for agriculture is becoming increasingly scarce, rice production is threatened by water shortages (Bouman 2007). Asia contributes more than 90 % of the world's total rice production while using more than 90 % of total irrigation water (Khepar et al. 2000).

It was estimated that by 2025, 15 million of Asia's 130 million ha of irrigated rice area may experience "physical water scarcity" and approximately 22 million ha of irrigated dry-season rice may suffer "economic water scarcity" (Tuong and Bouman 2003). This increasing water scarcity will require the development of alternative irrigated rice production systems that require less water than traditional flooded rice (Bouman et al. 2005). The challenge for sustainable rice production is to decrease the amount of water used while maintaining or increasing grain yields to meet the demands of an ever-growing population by improving water use efficiency (Yang and Zhang 2010).

Researchers have been developing various water-saving technologies for rice production systems, such as alternate wetting and drying (AWD) (Bouman and Tuong 2001; Belder et al. 2004), saturated soil culture (Tuong et al. 2004), direct dry seeding (Tabbal et al. 2002), and aerobic rice culture (Bouman et al. 2005; Kato et al. 2009). These have been found to be effective in reducing water use and improving water productivity, but there are still debates on whether these water-saving techniques will increase or decrease rice yields (Bouman et al. 2007). A common finding has been that irrigation rates can indeed be reduced without lowering grain yield (Yang et al. 2004; Zhang et al. 2009). However, thus far with conventional irrigated flooded rice production systems promoted by rice scientists at various research organizations, it has not been possible to obtain attractive increases in output that would provide farmers with the incentive to reduce their irrigation rates.

The system of rice intensification (SRI) which was developed in Madagascar and is now spreading in most Asian countries, and more recently in several African and Latin American countries, could potentially become an approach to increasing rice production with reduced water demand, thus improving both water use efficiency and water productivity (Stoop et al. 2002; Uphoff 2007, 2012). SRI principles focus on underutilized potentials for raising yields by changing farmers' agronomic practices toward more efficient use of their available land, water, and other resources (Uphoff 2003; Zhao et al. 2009).

While considerable evidence regarding the relevance of SRI to pro-poor development has become available, its scientific foundations have not been adequately pursued (Stoop 2011). SRI recommends keeping paddy soils moist but not continuously flooded, either by making minimum daily applications of water (saturated soil culture, SSC) or by alternately wetting and drying the fields (AWD). SRI practices, which transplant very young seedlings with much wider spacing and reduced plant populations and with active soil aeration, have been reported to increase the yields of irrigated rice by 25–50 %, or more, while reducing water requirements (Kassam et al. 2011; Satyanarayana et al. 2007; Thakur et al. 2011).

AWD is a broad term which should be defined in terms of the respective periods of wetting and drying introduced, as their impact on grain yield can be expected to vary. "Safe" AWD should reduce farmers' water demand by a small to a considerable amount without imposing any yield penalty. Little research has been done to quantify the impact of different degrees of AWD on grain yield and on water savings in rice, and even less research has considered the effects of making concurrent changes in crop management practices.

Most of the research findings on optimum water provision for paddy rice presently reported in the literature may not apply to SRI rice crops because its plants have profuse, longer-lived, and healthier root systems which are in contrast with the degraded and truncated root systems of flooded rice plants (Kassam et al. 2011). Accordingly, there may be scope, with use of SRI methods, for making still further reductions in the amount of water needed for efficient paddy rice production. Understanding the effects of agricultural water irrigation regimes on root growth and the physiology of rice plants, especially when different management systems are employed, is critical to raise both water and rice crop productivity.

The present study was carried out to investigate the impact of continuous versus alternate flooding of paddy fields on the resulting grain yield, root growth, and water productivity achieved under two alternative crop management systems, namely, SRI and a conventional transplanting system (CTS) of rice production that follows standard management practices.

Materials and methods

Site description

These experiments were conducted over 2 years at the Deras Research Farm, Mendhasal in Khurda district, Odisha, India (20°30′N, 87°48′10″E), during the 2009 and 2010 dry seasons (January–May). The soil of the experimental site has been classified as *Aeric Haplaquepts*, sandy clay loam in texture (63 % sand, 16 % silt, and 21 % clay), with pH of 5.6.

Experimental design and treatments

The experimental design was split-plot with three replications having subplot sizes of 15 × 10 m. In the main plots, rice was grown under the two crop production systems being assessed: the SRI and a conventional transplanting system (CTS) with standard management practices enumerated below. Five different water management treatments were used in the subplots: CF (continuous flooding), and water applications made 1, 3, 5, or 7 days after the disappearance of ponded water (DAD). All plots were surrounded by 50-cm-wide bunds to prevent lateral water seepage and nutrient diffusion between plots, followed by 50-cm-wide channels for irrigation.

Crop management

A medium-duration rice variety was used for the experiment (Surendra, 130–135 days), commonly grown by farmers in the region. Germinated seeds were broadcasted for the nursery on January 5, 2009 in the first year and on January 7, 2010 in the second year. Fertilizer use was standard across all plots—FYM at 5 t ha^{-1} along with chemical fertilizer: urea (80 kg N ha^{-1}), single super phosphate (40 kg P_2O_5 ha^{-1}), and muriate of potash (40 kg K_2O ha^{-1})—so that fertilization practices were not a variable in the evaluation.

The entire amount of P was applied at the time of the final land preparation, while N and K were applied in three splits, i.e., 25 % at 10 days after transplanting (DAT), 50 % at the tillering stage, and 25 % at the panicle initiation stage. We know that the SRI recommendation is for organic fertilization in preference to chemical fertilization, but in this evaluation, we did not make this practice an additional factor to be assessed. While soil nutrient amendments were not treated as a variable in either amount or form, it should be recognized that variations in these elements would interact with both the *cultivation system* and *water management* factors being tested by the experiments.

For the SRI plots, 12-day-old single seedlings at a spacing of 20 × 20 cm were transplanted within 30 min after removal from the nursery on January 17, 2009 and January 19, 2010. For CTS plots, three seedlings hill^{-1} of 25-day-old plants were transplanted at a spacing of 20 × 10 cm on January 30, 2009 and February 1, 2010. Plant densities for the two sets of trials were 25 and 150 plants m^{-2} for SRI and CTS, respectively. CTS plots thus had six times more plants on an area basis. The SRI plots were weeded by cono-weeder at 10, 20, and 30 DAT, while the CTS plots had three hand weedings at the same DAT intervals. Note that previous studies had shown the 20 × 20 cm spacing to be optimum with the other SRI practices under the local soil and climatic conditions rather than the 25 × 25 cm spacing usually recommended for SRI practice (Thakur et al. 2010a).

Irrigation management

Water was supplied through a cemented channel to a plot channel and subsequently to the plots themselves. First irrigation in the SRI plots was applied 5 DAT to moisten the field without ponding, and the different water management treatments were then applied beginning at 10 DAT. In the CTS plots, there was 5–7 cm of standing water during transplanting, and after disappearance of this ponded water, different water management treatments were applied. In the continuously flooded treatment, a water depth of 5–6 cm was maintained throughout the vegetative stage, while for the other treatments, each irrigation was applied according to the time interval specified for the treatment, until a 5-cm ponding depth of water was established in the field, and then the next irrigation was given as per the treatment schedule. The various irrigation treatments were continued during the entire vegetative stage of the crop. After panicle initiation, all plots were kept flooded with a thin layer of water 1–2 cm on the paddies, and all were drained 15 days before harvest.

Sampling and measurements

Three hills were randomly selected from each replicate at the grain-filling stage for root sampling. Root samples were collected through the monolith method used to remove soil to a depth of 30 cm along with the hill. Roots were carefully washed, dried in an oven at 65 °C, and root weight was recorded. For measurement of xylem exudation rate at the grain-filling stage, three hills with an average number of panicles were randomly selected from each plot replicate. Each stem was cut at 10 cm from the soil surface, and pre-weighed cotton wool packed in a polythene bag was attached with tape to the cut end of the hill. After 24 h, each bag was detached, sealed, and weighed, and the weight of the root exudates was calculated by subtracting the weight of the bag and pre-weighed cotton wool (San-oh et al. 2004).

At the grain-filling stage, five flag leaves and the same number of fourth leaves (from the top) were used to measure the photosynthesis rate in each plot by using a CIRAS-2 Portable Photosynthesis System (PP Systems, UK).

All plants in an area of 3 × 3 m for each plot were harvested (excluding the border rows) for determination of yield per unit area. Grain yield was adjusted to 14.5 % seed moisture content. Average tiller number and panicle number were determined at harvesting from a representative square meter area from each plot. Likewise, panicle length, number of grains per panicle, and number of filled grains were measured for each panicle individually harvested from a square meter area. The percent of ripened grains was calculated by dividing the number of filled grains by the number of total grains.

Trapezoidal RBC flumes (13.17.02 RBC, Eijkelkamp Agrisearch Equipment, The Netherlands) were installed in the cemented channel and were used to estimate the water supplied to each plot by reading flume water height at 2–5-min intervals, converting these measures to volume, and integrating these for the irrigation period. The quantity of water applied during each irrigation was summed to calculate the total amount of water applied to each plot throughout the cropping season. Water productivity was estimated as grain yield divided by total water utilized (rainfall and applied) and expressed as kg ha-mm^{-1}.

Statistical analysis

Data were statistically analyzed using the analysis of variance (ANOVA) technique as applicable to split-plot design (Gomez and Gomez 1984). Duncan's multiple range test (DMRT) was employed to assess differences between the treatment means at the 5 % probability level. All statistical analyses were performed using SAS 9.2 for Windows (SAS Institute Inc., Cary, NC, USA).

Results

Grain yield and yield components

SRI across all of the water management treatments produced on average grain yield 49 % higher than CTS. Water management treatments were found to significantly affect grain yields. Compared with continuous flooding, 1-DAD to 5-DAD treatments gave higher grain yield under SRI (Fig. 1). With SRI, the highest grain was produced under the 3-DAD treatment, and there was no significant difference in grain yield between the 1-DAD and 3-DAD treatments. However, with CTS, the most grain was produced with the 1-DAD treatment, a yield comparable to the lowest grain yield under SRI (produced with 7-DAD treatment). Continuous flooding and 3-DAD water management produced similar grain yields under the CTS method. For both cultivation systems, the lowest yield was observed from 7-DAD plots.

When we compared the changes in grain yield with continuously flooded rice as a baseline (Fig. 2), under CTS, the 1-DAD treatment gave 3.2 % higher grain yield, but in the 3-DAD, 5-DAD, and 7-DAD plots, grain yield decreased by 3 %, 9 %, and 44 %, respectively, compared with the CF yield. In the case of SRI, on the other hand, 1-DAD, 3-DAD, and 5-DAD plots produced grain yields, respectively, 14, 16, and 6 % higher than with CF. However, for SRI at 7-DAD, there was 22 % less grain produced compared to CF. These results indicated that with AWD irrigation under CTS, grain yield starts declining beyond 1-DAD. However, for rice crop grown under SRI, AWD significantly increased yield up to 5-DAD compared to CF irrigation, and only beyond 5-DAD did grain yield start decreasing, when SRI plants encountered moisture stress. Even so, the grain yield at 7-DAD under SRI (4.28 t ha^{-1}) remained equal to or superior than any of the CTS yields (Fig. 1).

Yield components like number of grains panicle^{-1}, spikelet fertility, and 1,000-grain weight varied significantly in response to the methods of rice cultivation and the associated water management practices. On average, across all water treatments, SRI rice plants had 32 % longer panicles containing 29 % more grains, with significantly higher grain filling and more grain weight, compared to plants grown with CTS methods (Table 1). Under SRI management, grains panicle^{-1} was significantly higher in 1-DAD and 3-DAD treatments compared with other water management treatments. In contrast, under CTS, grains per panicle were higher with CF and 1-DAD compared to other water management treatments. Grain filling was significantly greater in 1-DAD and 3-DAD treatments than the CF and 5-DAD treatments. With the highest water stress at 7-DAD, grain filling was severely reduced under both cultivation systems, 45 % under CTS and 22 % under SRI compared with CF.

Tillering and panicle formation

The cultivation systems significantly affected the number of tillers and panicles per hill; with SRI, these were double compared to crops grown under CTS (Table 2). Water management treatments had no effect on the number of tillers per hill, but they had an effect on the number of panicles hill^{-1}. This parameter was significantly increased with AWD treatments compared to continuous flooding, especially under SRI (except for 7-DAD). Under CTS, there was little or no effect on the number of panicles in response to changes made in water management practices.

Due to the greater number of hills per unit area under CTS compared with SRI, there were no significant differences between these two cultivation systems in the number of tillers m^{-2}. However, the number of panicles

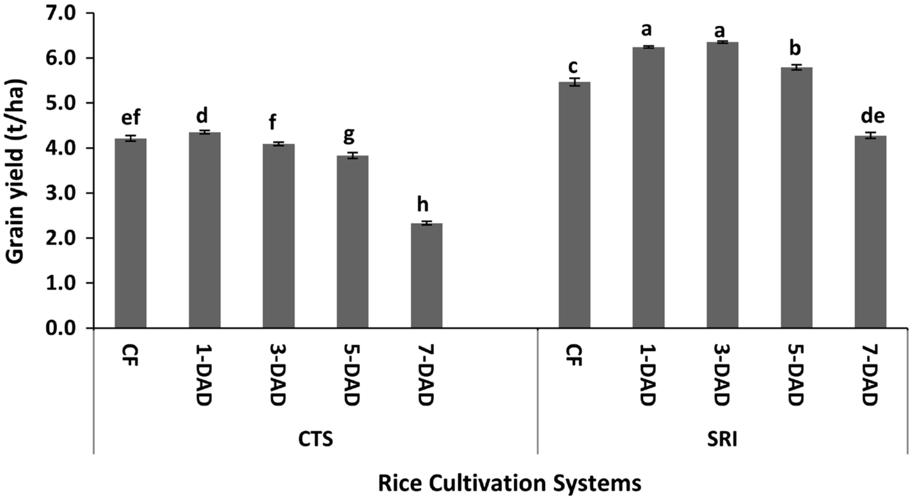

Fig. 1 Effects of rice cultivation systems and water management on grain yield. *Vertical bars* represent the standard deviation ($n = 15$). (*CTS* conventional transplanting system, *SRI* system of rice intensification, *CF* continuous flooding, *DAD* days after disappearance of ponded water)

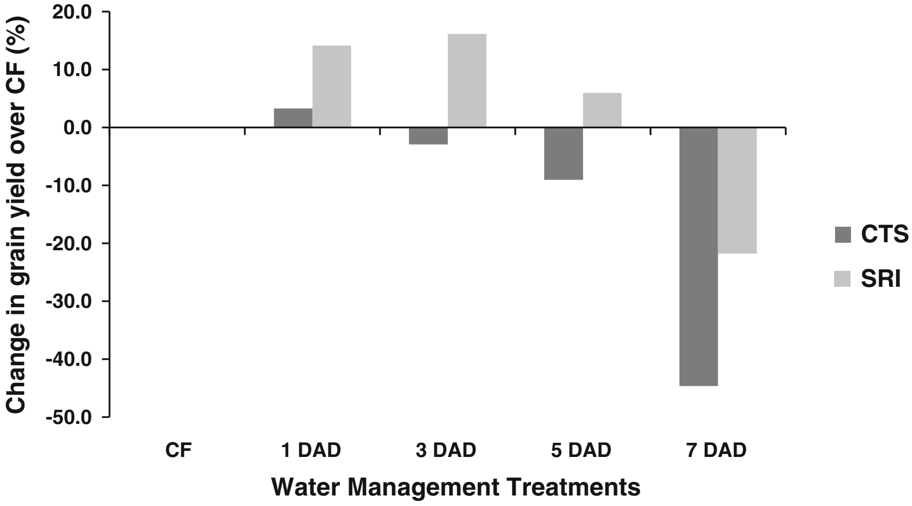

Fig. 2 Effects of water management practices on change in grain yield over continuously flooded rice under SRI and CTS of rice cultivation systems. (*CTS* conventional transplanting system, *SRI* system of rice intensification, *CF* continuous flooding, *DAD* days after disappearance of ponded water)

Table 1 Effect of rice cultivation systems and water management on yield-contributing characteristics

Cultivation systems	Water management treatments	Ave. panicle length (cm)	Total grains panicle^{-1}	Grain filling (%)	1,000-grain weight (g)
CTS	CF	17.0 c	102.7 de	73.7 d	23.9 b
	1-DAD	17.8 c	107.5 d	80.3 c	23.9 b
	3-DAD	16.6 c	97.2 ef	78.8 c	24.1 b
	5-DAD	15.1 d	91.5 f	73.6 d	23.9 b
	7-DAD	14.3 d	78.5 g	70.5 e	23.2 c
	Ave.	16.2	95.5	75.4	23.8
SRI	CF	20.2 b	116.0 bc	85.3 b	24.5 a
	1-DAD	22.0 a	134.8 a	87.8 a	24.7 a
	3-DAD	22.3 a	133.2 a	89.8 a	24.7 a
	5-DAD	22.0 a	124.0 b	83.3 b	24.7 a
	7-DAD	20.3 b	109.2 cd	78.6 c	24.1 b
	Ave.	21.3	123.4	85.0	24.5
Analysis of variance					
Cultivation system (CS)		**	**	**	**
Water management (W)		**	**	**	**
CS × W		**	**	**	NS

Mean values followed by different letter within columns differ significantly at $p < 0.05$ according to Duncan's range test

CTS conventional transplanting system, *SRI* system of rice intensification, *CF* continuous flooding, *DAD* days after disappearance of ponded water, NS not significant

* $p < 0.05$; ** $p < 0.01$

m^{-2} was significantly greater in SRI plots, by 13 %, compared to CTS plots. This happened due to a significant improvement in the percentage of effective tillering under SRI. Under CTS, only 73.5 % of tillers formed panicles, whereas under SRI, this proportion was 82 %, a significant increase (12 %) in panicle formation with SRI crop management.

Water management treatments significantly affected the tiller and panicle numbers per unit area under both cultivation systems, and notably these were greater with AWD treatments than with CF, except for the 7-DAD treatment. Under CTS, the highest panicle number was found with 1-DAD and 3-DAD treatments; with SRI management, panicle number was the highest in 3-DAD treatment and significantly greater than for CF.

Root dry weight and xylem exudation rate

Roots' growth and their functionality were significantly affected by crop and water management practices. Rice plants grown with SRI practices had 2.5 times more root dry weight, twice the amount of exudates transported from roots toward shoots, and double the rates of exudation per hill compared to rice crops grown following CTS (Table 3). In spite of much lower plant populations under SRI, at the grain-filling stage on a unit area basis, SRI plots had 22 % more root dry weight and 5.7 % greater amount of exudates compared to CTS plots. These data clearly indicate better root growth and performance under SRI methodology during the grain-filling stage of the crop.

Table 2 Effect of rice cultivation systems and water management on tillering and panicle formation

Cultivation systems	Water management treatments	Per hill		Per unit area		Effective tiller (%)
		Tillers (no. hill^{-1})	Panicles (no. hill^{-1})	Tillers (no. m^{-2})	Panicles (no. m^{-2})	
CTS	CF	8.0 b	6.1 c	399.2 cd	281.0 g	70.5 d
	1-DAD	8.2 b	6.5 c	404.0 c	316.0 d	78.4 b
	3-DAD	8.2 b	6.3 c	409.8 abc	319.7 d	78.1 b
	5-DAD	8.5 b	5.8 c	417.8 ab	294.3 ef	70.5 d
	7-DAD	7.3 b	5.2 c	365.2 e	255.5 h	70.0 d
	Ave.	8.0	6.0	399.2	293.3	73.5
SRI	CF	15.3 a	12.2 b	385.5 de	302.8 e	78.5 b
	1-DAD	16.8 a	14.2 a	420.5 ab	355.0 b	84.5 a
	3-DAD	17.2 a	14.7 a	430.8 a	370.0 a	85.9 a
	5-DAD	16.0 a	13.7 a	402.3 c	341.0 c	85.0 a
	7-DAD	15.2 a	11.0 b	376.2 de	287.0 fg	76.5 c
	Ave.	16.1	13.1	403.1	331.2	82.1
Analysis of variance						
Cultivation system (CS)		**	**	NS	**	**
Water management (W)		NS	**	**	**	**
CS × W		NS	NS	**	**	**

Mean values followed by different letter within columns differ significantly at $p < 0.05$ according to Duncan's range test

CTS conventional transplanting system, *SRI* system of rice intensification, *CF* continuous flooding, *DAD* days after disappearance of ponded water, NS not significant

* $p < 0.05$; ** $p < 0.01$

Water management treatments also significantly affected the root growth and root activity of rice plants under the two different cultivation systems. AWD significantly enhanced root growth compared to continuously flooded rice, but only in treatments up to 5 DAD; beyond that, root growth was reduced. Under CTS, root growth per hill was observed to be significantly greater in 1-DAD than with other water management treatments. In contrast, under SRI, root growth was the highest in the 3-DAD treatments. Similarly, AWD treatments significantly enhanced the amount of xylem exudates and their transport rate per hill under both systems. Root growth and root activity were reduced in continuous flooding and 7-DAD treatments in both systems.

Photosynthetic rate during grain filling

We anticipated that variation in root growth and xylem exudation rates during grain filling under the different cultivation systems would alter the leaves' photosynthesis rate. The rate of photosynthesis of the flag and fourth leaves during the grain-filling stage was indeed found to be significantly different between the SRI and CTS systems of rice cultivation (Fig. 3). Overall, across all water management regimes, the flag leaf and fourth leaf of SRI plants had photosynthesis rates 23 and 18 % higher, respectively, compared to the flag and fourth leaves of CTS plants.

The highest rate of photosynthesis in both flag and fourth leaves was found with 1-DAD and 3-DAD treatments under both SRI and CTS. Continuously flooded and 5-DAD treatments had similar rates of photosynthesis in the flag leaf under both cultivation systems. Not surprisingly, the lowest photosynthetic rate was found in plants grown under the highest water-stress treatment, i.e., 7-DAD.

Water requirements and productivity

During the entire cropping season (January–May), 70 and 45 mm of rainfall occurred in 2009 and 2010, respectively. Therefore, crops got their water mostly through irrigation. Evapo-transpiration values were calculated as 2.5–6.5 mm day^{-1} in 2009 and 2.7–6.1 mm day^{-1} in 2010 during the crop growth period.

Across all water management treatments, the total water used in CTS was 1,143 mm; with SRI management, 984 mm of water was used during the entire crop growth period. This was a 14 % saving of water with SRI compared to CTS (Table 4). Among different water management treatments, the most water was required with continuous flooding and the lowest with 7-DAD treatment under both methods of cultivation. The water savings observed under AWD treatments resulted from reduced seepage and percolation, and higher evaporative losses from the continuously flooded plots.

Overall, throughout all the water management treatments, significantly higher grain per unit quantity of water applied was produced under SRI (5.7 kg ha-mm^{-1}) as compared to CTS, which produced only 3.3-kg grain from the same amount of water. This means that SRI rice plants

Table 3 Effect of rice cultivation systems and water management on root dry weight and xylem exudation rates at grain-filling stage

Cultivation systems	Water management treatments	Per hill			Per unit area		
		Root dry weight (g hill^{-1})	Exudate amount (g hill^{-1})	Rate (g hill^{-1} h^{-1})	Root dry weight (g m^{-2})	Exudate amount (g m^{-2})	Rate (g m^{-2} h^{-1})
CTS	CF	6.1 ef	2.5 fg	0.10 f	306.0 e	125.7 e	5.2 de
	1-DAD	8.5 d	3.4 e	0.14 d	426.5 b	170.8 b	7.1 b
	3-DAD	6.7 e	2.9 f	0.12 e	334.0 d	143.7 cd	6.0 c
	5-DAD	6.7 e	2.8 f	0.12 e	333.2 d	138.0 d	5.8 cd
	7-DAD	5.5 f	2.1 g	0.09 f	274.5 f	107.0 f	4.5 f
	Ave.	6.7	2.7	0.11	334.8	137.0	5.7
SRI	CF	14.7 b	4.9 c	0.20 c	367.5 c	122.6 e	5.1 ef
	1-DAD	17.9 a	6.2 b	0.26 b	447.2 ab	154.3 c	6.4 c
	3-DAD	17.6 a	7.8 a	0.32 a	439.6 ab	194.8 a	8.1 a
	5-DAD	18.5 a	5.8 b	0.24 b	462.7 a	144.6 cd	6.0 c
	7-DAD	13.4 c	4.3 d	0.18 c	334.7 d	108.3 f	4.5 f
	Ave.	16.4	5.8	0.24	410.4	144.9	6.0
Analysis of variance							
Cultivation system (CS)		**	**	**	**	*	*
Water management (W)		**	**	**	**	**	**
CS × W		**	**	**	**	**	**

Mean values followed by different letter within columns differ significantly at $p < 0.05$ according to Duncan's range test

CTS conventional transplanting system, *SRI* system of rice intensification, *CF* continuous flooding, *DAD* days after disappearance of ponded water

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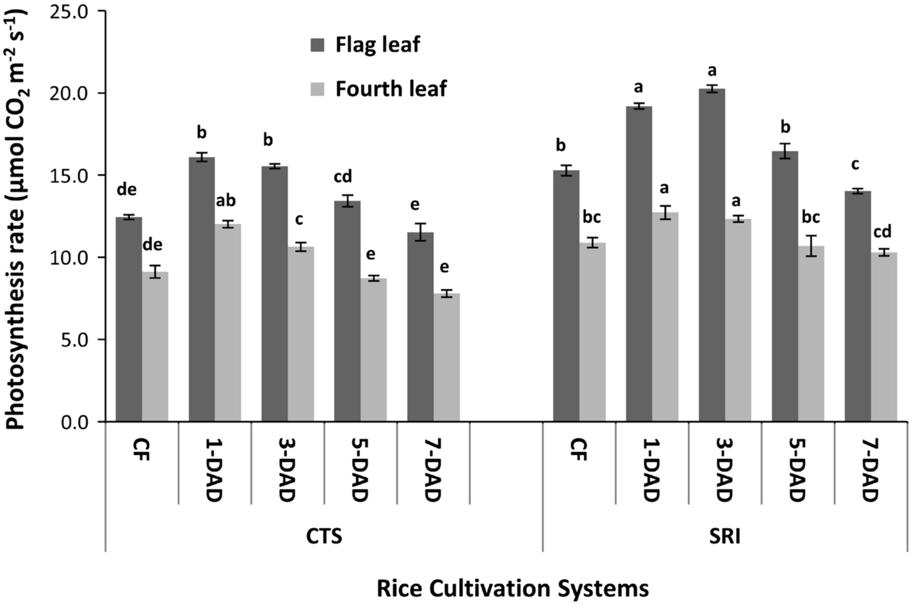

Fig. 3 Effect of rice cultivation systems and water management on photosynthesis rate of flag and fourth leaf at grain-filling stage. For each replicate, five flag and fourth leaves (from *top*) were used for the measurements. *Vertical bars* represent the standard deviation ($n = 15$). *Bars* with a *different letter* are significantly different at the 5 % level. (*CTS* conventional transplanting system, *SRI* system of rice intensification, *CF* continuous flooding, *DAD* days after disappearance of ponded water)

were 75 % more efficient in utilizing water for grain production (Table 4). Under CTS, the highest water productivity was obtained with the 1-DAD treatment (3.73 kg ha-mm^{-1}), while under SRI, it was achieved in the 3-DAD treatment plots (6.47 kg ha-mm^{-1}).

Discussion

In our study, we noticed a significant impact of the two rice cultivation systems (SRI vs. CTS), of different water management practices, and of their interaction effects on plants' phenotypes, their physiological performances, grain yield, and water productivity.

Impact of cultivation systems

The impact of SRI management on grain yield enhancement has been reported from several countries (Kassam et al. 2011). Previous literature reports have well documented the effect of individual practices associated with SRI for obtaining higher yields of irrigated rice, e.g., use of single seedlings (San-oh et al. 2006), younger seedlings (Pasuquin et al. 2008; Menete et al. 2008), AWD irrigation (Zhang et al. 2009), and organic fertilization (Yang et al. 2004).

In the present study, across all water management treatments, SRI produced 49 % higher grain yield compared with CTS (Fig. 1). Yield enhancement under SRI practice can be attributed to better plant phenotypes (vigorous root growth and tillering) and to enhanced physiological performance of the individual hills in terms of maintaining a greater xylem exudation rate and higher leaf photosynthetic rate during the grain-filling stage of crop growth. Transplanting single and younger seedling with AWD irrigation improves root growth and its activity under SRI (Mishra and Salokhe 2010; Zhang et al. 2009). Previous research studies have also shown that SRI methods result in more vigorous growth of roots and enhanced xylem exudation rate in the rice crop (Hameed et al. 2011; Thakur et al. 2010b, 2011). Barison and Uphoff (2011) documented vigorous root growth under SRI management as assessed by root-pulling resistance, with SRI plants offering as much as 8 times more resistance per plant for uprooting than was measured with conventionally grown plants.

The greater number of tillers and panicles with SRI might be largely due to wider spacing and also to the transplanting of young and single seedlings that are able to complete more phyllochrons of growth before anthesis due to their more favorable growing conditions above and below ground compared to rice grown under CTS (Nemoto

Table 4 Effect of rice cultivation systems and water management on total water use and its productivity

Cultivation systems	Water management treatments	Total water use (mm)[a]			Water productivity (kg ha-mm^{-1})		
		2009	2010	Mean	2009	2010	Mean
CTS	CF	1,198.4	1,211.4	1,204.9 a	3.52	3.48	3.50 f
	1-DAD	1,162.3	1,172.3	1,167.3 b	3.73	3.72	3.73 e
	3-DAD	1,126.4	1,145.2	1,135.8 c	3.60	3.61	3.60 e
	5-DAD	1,109.2	1,115.2	1,112.2 d	3.46	3.43	3.45 f
	7-DAD	1,087.1	1,100.7	1,093.9 d	2.10	2.16	2.13 g
	Ave	1,132.7	1,145.0	1,142.8	3.3	3.3	3.3
SRI	CF	1,035.2	1,050.5	1,042.9 e	5.31	5.17	5.24 c
	1-DAD	1,005.6	1,015.1	1,010.4 f	6.23	6.12	6.17 b
	3-DAD	976.2	985.8	981.0 g	6.53	6.41	6.47 a
	5-DAD	948.4	955.2	951.8 h	6.11	6.05	6.08 b
	7-DAD	935.6	935.3	935.5 h	4.59	4.55	4.57 d
	Ave.	980.2	988.4	984.3	5.8	5.7	5.7
Analysis of variance							
Cultivation system (CS)				**			**
Water management (W)				**			**
CS × W				NS			**

Mean values followed by different letter within columns differ significantly at $p < 0.05$ according to Duncan's range test

CTS conventional transplanting system, *SRI* system of rice intensification, *CF* continuous flooding, *DAD* days after disappearance of ponded water, NS not significant

* $p < 0.05$; ** $p < 0.01$

[a] Rainfall of 2009 and 2010 was 70.0 and 45.0 mm during cropping season, respectively

et al. 1995; Stoop et al. 2002; Thakur et al. 2010b). This results in more and more productive tillers as well as in larger root systems (Tables 1 and 2). Under SRI, every tiller also had more duration to grow and develop due to earlier emergence; its resulting ability to form panicles is thus much higher than for rice plants grown under CTS. Vigorous roots with higher supply of resources from soil to shoots are responsible for more tillers forming panicles (Mishra et al. 2006) and for improvement in the physiological efficiency of rice plants (Mishra and Salokhe, 2010; Thakur et al. 2010a).

Maintenance of higher rates of photosynthesis during the grain-filling stage contributed to increased dry weight of plants and to a prolonged grain-filling process in SRI plants as compared with CTS plants. This led also to heavier individual grains in the former. Likewise, delayed senescence, as indicated by the higher photosynthetic rate maintained in the fourth leaf (lower leaf) of SRI plants, would enable the plant to transport more photosynthates to its roots, leading to a prolonged period of root growth and functioning that will affect positively the photosynthesis and metabolism processes in the canopy (Toriyama and Ando 2011; Thakur et al. 2013).

The two cultivation systems evaluated in this study represent a considerable divergence in cultural practices, mainly in seedling age, plant density, and active soil aeration (mechanical weeding). As noted above, the effects of enriching the organic matter content of the soil, as recommended with SRI, were not evaluated as a separate management practice/factor. Therefore, rice plant responses to water management will be interactive with the effects of other practices, notably plant density, which complicates the data interpretation for the present set of experiments. Nevertheless, the present study clearly demonstrates that SRI with just one-sixth as many plants m^{-2} had significant positive effects on the plants' phenotype and physiological performance as compared with the much higher planting density under CTS. With its high plant density, CTS leads to greatly diminished root systems per individual plant and therefore to reduced water and nutrient uptake which causes plants to function far less effectively. As already reported by Kar et al. (1974), root systems affected by hypoxia become less healthy and active, which explains at least in part why rice plants under CTS become more vulnerable to drought stress and show a diminished physiological functioning.

Recently, there has been more emphasis placed on increasing water productivity than on increasing water use efficiency (Kassam et al. 2007). Such improvements would enable farmers to produce more grain with relatively less water. With SRI, the significant increase in grain yield using 14 % less water resulted in enhanced water productivity by 73 %, increasing from 3.3 to 5.7 kg ha-mm^{-1}.

Impact of water management

Instead of keeping rice fields continuously flooded, the adoption of AWD methods means that irrigation water is applied to fields to restore flooded conditions on an intermittent basis, only after a certain number of days have passed since the disappearance of ponded (standing) water. Under AWD, the number of days of non-flooded soil before the next irrigation is applied can vary from 1 day to more than 10 days (Bouman et al. 2007). According to the analysis of Bouman and Tuong (2001), in most cases, AWD treatments result in yield reductions compared with continuously flooded treatment; however, increased water productivity is achieved because there are larger reductions in water input relative to reductions in yield. They report that differences in the number of days between irrigations and in soil and hydrological conditions cause large variability in the results of AWD.

However, a number of recent reports have shown beneficial effects from practicing AWD over continuous flooding apart from water saving, provided that there are other, appropriate changes made in crop management, besides the water regimes. Sato and Uphoff (2007) reported from Indonesian experience that continuous submergence was not essential for achieving high rice yields. AWD irrigation methods can result in greater and deeper root systems, enhancing nutrient uptake (Yang et al. 2004) and raising water use efficiency and grain yield (Zhang et al. 2009). Yang et al. (2004) also reported that the beneficial effects of integrated nutrient management for rice yield are significantly decreased by waterlogging of rice fields.

Apparently, an aerobic/AWD soil condition will significantly affect a diverse range of plant physiological processes. In that respect, Zhang et al. (2009) reported that moderate wetting and drying soil conditions significantly increase root oxidation activity, cytokinin concentrations in the roots and shoots, leaf photosynthetic rate, and activities of key enzymes involved in sucrose-to-starch conversion in grains. Similarly, San-oh et al. (2006) showed that greater root growth is responsible for more transport of cytokinins via the xylem up to the leaves for maintenance of higher rates of photosynthesis.

Comparable results were obtained in the present study which showed that under both cultivation systems, AWD treatments like 1-DAD and 3-DAD showed improvements in root growth and activity, photosynthesis rate, grain filling, and ultimately water productivity, compared to continuous flooding. But, as expected, when going beyond moderate water stress, the rate of photosynthesis was seen to decline, leading to reduced root growth and poorer grain filling, resulting in lower grain yield.

Interaction effects of cultivation systems and water management

SRI practices include not flooding rice fields during the vegetative stage of crop growth. Previous comparisons therefore were made between SRI with AWD irrigation versus flooded conventional practice. In the present study, similar types of water management were compared between SRI and CTS; therefore, water saving in SRI was only 14 %, which is not as large as has been found by other researchers (Satyanarayana et al. 2007; Singh 2013; Suryavanshi et al. 2013). Averaging in results of SRI crop management with continuous flooding reduces the effect of the other SRI practices. Chapagain and Yamaji (2010) found a 28 % saving of irrigation water, without reducing grain yield, when using AWD irrigation practice with SRI crop, soil, and nutrient management. In their evaluations, Krupnik et al. (2012) and Singh (2013) found no yield difference between SRI and the standard management practice of flooded rice; but with SRI, they found there were water savings and significant increases in water productivity. Some experiments in China have shown significant improvements in yield as well as in water use efficiency and in irrigation water use efficiency under SRI compared with the traditional flooding method of rice cultivation (Lin et al. 2009; Zhao et al. 2009).

When comparing similar water management treatments under both SRI and CTS, the overall water requirement was found to be less under SRI. The reduced requirement of water under SRI was mainly due to reduced water requirements for the nursery (for SRI, only 1/10th as much area is needed compared with CTS, and SRI seedlings spend only two weeks in the nursery, not three or more). Further, in the main field for tillage operations under SRI, there was no need for standing water while transplanting. Also with SRI methods, just 12 days were required to complete all land preparation activities like land soaking, plowing, and leveling, which for conventional transplanting system took 21–25 days.

In conventional transplanting, farmers start their water use in the main field for land soaking about the same time or soon after they start to prepare their nursery for raising seedlings. They continue to use water in the main field until the seedlings are ready for transplanting. Thus, large amounts of water are lost from the main field through evaporation, seepage, and percolation and from surface runoff. Also, the SRI crop usually matures 5-7 days earlier than in the conventional system (even with higher yield) because the young SRI seedlings experience less transplanting shock and thus recover quickly. Water is thus saved with an overall reduction in the crop growth period. However, the SRI crop remains in the main field for a longer period (6-8 days) due to its being transplanting from the nursery into the main field at 12 days rather than 25 days, so the water requirements in the main field are a little higher than with CTS.

The effects of water management treatments on root growth, photosynthetic rate, and grain yield differed significantly between the two cultivation systems and would explain the beneficial responses under SRI. Under CTS compared with SRI management, all five water management treatments caused poorer root growth, tillering, panicle formation, grain panicle^{-1}, grain filling, and grain weight.

It is evident from these results that AWD had beneficial effects on grain yield compared with continuous flooding and especially so under SRI management practices. Under the conventional cultivation practice, the highest grain yield and greatest water productivity were found with the 1-DAD treatment, while under SRI, these parameters were the highest with 3-DAD. With CTS, grain yield started declining beyond 1-DAD in comparison to standard flooding of rice mainly due to poor root growth; in contrast, SRI productivity started to decline only beyond the 5-DAD treatment. This also indicates that SRI crops are more tolerant of water stress than CTS crops and that they are able to give greater grain yield even with lesser application of water due to their more vigorous root growth, their greater root activity, and a higher rate of photosynthesis in their canopies. A major reason for these recorded differences would have been the drastic reduction in the number of rice plants/square meter under SRI.

Conclusions

The challenges to sustaining or maintaining rice productivity are presently increasing as there is greater scarcity of water and more competition for water resources. This study has shown that certain crop management practices can concurrently achieve the dual goals of increasing grain production and reducing the water requirements for irrigated paddy rice. It is concluded that in this increasingly water-scarce world, SRI offers opportunities to reduce rice farmers' need for water while enhancing their grain production. In the context of the present concerns about feeding a growing world population, and about the anticipated future shortages of irrigation water in many rice-producing areas, the presented results merit further exploration through a comprehensive research program.

Total rice production can also be increased by being able to use water saved in one location to irrigate land area in another place, although the amounts and timings of water application always need to be locally determined and adjusted to local soil type, depth of the groundwater table, and environmental conditions. Water is not an easily fungible resource, and the hydrological dynamics of water across time and place need to be taken into account. Further study on various components of water balance measurements of rice water requirements under SRI is needed. Comparative studies on SRI's yield and water productivity performance vis-à-vis other water-saving rice management systems should also be investigated in the future.

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