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Enhancing water and cropping productivity through Integrated System of Rice Intensification (ISRI) with aquaculture and horticulture under rainfed conditions

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ABSTRACT

The System of Rice Intensification (SRI), based on modifications in the management practices for rice cultivation, is being utilized in many countries, although not without some controversy. One reason cited for non-adoption or disadoption of SRI is difficulties with water management under rainfed conditions with unreliable or aberrant rainfall distribution, which causes either flooding or long dry spells, or both. These constraints could be dealt with by tapping groundwater resources or by capture and use of rainwater runoff and/or by diversification of the farming system.

A 2-year field experiment was conducted in Odisha, India to evaluate SRI under rainfed conditions and also to explore options for enhancing the economic productivity of land and water under such conditions. Four rice cropping systems were evaluated: (i) conventional rice cultivation under rainfed conditions, (ii) SRI methods as adapted to rainfed cultivation, (iii) rainfed SRI methods with drainage facilities and supplementary pump-irrigation, and (iv) integrated SRI (ISRI) where rainwater runoff was harvested and stored for aquaculture and horticulture crops while also providing supplementary irrigation for the rice crop.

The rice crop grown with adapted SRI practices under rainfed condition showed significant improvements in the plants' morphology and physiology. Phenotypic changes included: greater plant height and tillering, more number of leaves, and expanded root systems. These changes were accompanied by changes in plants' physiological functions like greater xylem exudation rate and more light interception by the canopy, increased chlorophyll content in the leaves, and higher light utilization and photosynthetic rates during flowering. These factors were responsible for improved yield-contributing characteristics and for higher grain yield (52%) as compared with crops grown by conventional production methods. Comparing yield from rainfed conventional vs. SRI methods between drought and normal-rainfall years indicated that the latter methods are more drought-tolerant and productive; greatly expanded and active root systems with SRI have been important contributing factors.

Introducing drainage and supplementary irrigation improved both the grain yield (by 29%) and water productivity for rainfed SRI. Further, integrating aquaculture and horticulture with SRI management and rainwater harvesting increased the rice yield further (by 8%) and the net water productivity. This integrated system was found to raise the net income per unit of water by more than 60-fold compared to conventional rainfed rice cultivation. This option looks promising for improving food security for smallholders under erratic or diminished rainfall conditions.

1. Introduction

Food security is threatened by continuing population growth, declining arable land per capita, and water scarcity (Fedoroff et al., 2010; Satterthwaite et al., 2010), with these effects being exacerbated by the phenomena of climate change (Wheeler and von Braun, 2013). In recent years farmers have been experiencing declining growth of productivity, which is associated with several widespread phenomena such as land degradation, soil

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fertility loss, salinization, erratic rainfall, and extreme weather events (IFPRI, 2009). In the near future, farmers and their agricultural systems need to be able to cope with more frequent incidences of extreme weather events due to climate change (Gornall et al., 2010; Lobell et al., 2009; Meinke et al., 2009; Naylor et al., 2007).

In rainfed areas, which amount to about 54 million ha worldwide, with a lack of irrigation facilities, rainfall is the only source of water for a rice crop that is grown just once a year, during the rainy season (Bouman et al., 2007). Due to uneven and unreliable rainfall distribution over the cropping season, either most of the rainwater from heavy downpours runs off and is lost from the rice fields, or long dry spells result in low productivity. Common features of rainfed rice production include low productivity (both crop and water), poor fertilizer use-efficiency, and environmental pollution.

To meet rising food demand we need to increase the sustainability of food production in socially acceptable ways and from diminishing land and water resources (Schneider et al., 2011; Swaminathan, 2007). Agriculture systems will need to evolve by intensifying production from available land, while practicing water-efficient techniques that will sustain also the associated ecosystems (Fedoroff et al., 2010; Giovannucci et al., 2012) under a changing climate (Gornall et al., 2010; Meinke et al., 2009; Naylor et al., 2007).

1.1. *Water management alternatives in rice cultivation*

A number of rice production systems that use various water-saving irrigation practices have been proposed to deal with such constraints, including alternate wetting and drying (Belder et al., 2004, 2007; Bouman and Tuong, 2001; Zhang et al., 2008); continuous soil saturation (Tuong et al., 2004); sprinkler irrigation (Muirhead et al., 1989); direct-dry seeding systems that use less water (Tabbal et al., 2002); and aerobic rice culture (Kato et al., 2009; Nie et al., 2012). However, they all too often involve some reduction in grain yield, increased costs of production, and a need for very precise control over irrigation water (Bouman et al., 2007).

Some of the above reports have shown alternate wetting and drying (AWD) by itself reducing rather than increasing grain yield due to nitrogen loss, shoot biomass reductions, and a shortened grain-filling period (Belder et al., 2004; Tabbal et al., 2002). Conversely, some other reports have shown AWD able to maintain or even increase grain yield because of enhanced growth of roots (Yang et al., 2007), a higher grain-filling rate, and remobilization of carbon reserves from the vegetative tissues into grains (Zhang et al., 2008, 2009). Overall, changing from continuously flooded to a more-aerobic rice culture also has implications for other aspects of the rice production system, including nutrient dynamics and weed control. Excessive water use in rice cultivation not only lowers water productivity, but also increases NO_3-N leaching, causing environmental pollution by contaminating ground and surface water resources.

1.2. *System of Rice Intensification: general background and major principles*

The System of Rice Intensification (SRI), initially developed in Madagascar (Laulanié, 1993), has been extended to more than 50 countries by governmental and non-governmental organizations (http://sri.ciifad.cornell.edu/). SRI has been characterized as a natural resource management technology for enhancing crop yield using less water and other inputs, making it particularly relevant for smallholding farmers (Noltze et al., 2012; Stoop et al., 2002; Uphoff, 2003).

SRI principles focus on neglected biological and natural resource potentials and processes to raise yields through adjustments in farmers' agronomic practices resulting in large efficiency and production gains (Uphoff, 2007). SRI practices diverge from conventional agronomic management for irrigated rice and include: (a) transplanting young seedlings, preferably 8–12 days old (at 2–3 leaf stage), quickly, carefully, and at shallow depth (1–2 cm deep), (b) transplanting single, widely-spaced seedlings in a square pattern, thereby greatly reducing plant populations, (c) maintaining mostly aerobic soil conditions rather than continuous flooding of fields during the vegetative growth period, (d) preferably using organic manures like compost or mulch, and (e) controlling weeds with a mechanical hand weeder that actively aerates the soil surface (Stoop et al., 2002). These practices enhance root system development and root growth and hence the plants' interactions with the soil biota.

1.3. *The dilemmas of rainfed rice cultivation and relevance of SRI principles*

Conventional water management for rice has kept paddy fields continuously submerged. However, SRI practice reduced water requirements, keeping paddy soils moist but not continuously flooded, either by making minimum daily applications of water or by alternately wetting and drying the field (Stoop et al., 2002).

Unreliable rainfall distribution over the cropping season, a condition that is very common for much of rice cultivation in India and other rice-growing countries, has a significant impact on rainfed rice cultivation and results. Due to the uncertainty of rainfall, many rice farmers go for direct dry-seeding instead of transplanting method. Very high seed rates in direct seeding ($>100\ \mathrm{kg\ ha^{-1}}$) increase the competition among plants for growth resources, resulting in poor root growth and anchorage, lodging, and low grain yield. On the other hand for transplanting, farmers often use over-aged seedlings when the onset of the rains is delayed. When seedlings have to stay in the nursery for weeks, less time remains for their development and to complete their growth cycle in the main field, which automatically translates into yield losses.

Another frequent problem in rainfed rice cultivation is to control and to avoid crop damage by excess water from heavy downpours. Conversely, when there is insufficient rain, however, crops suffer drought stress. Both situations will hamper root growth and tillering, which ultimately result in reduced grain yields.

During the rainy season, it is quite difficult to practice any water-saving irrigation methods. This applies certainly to the SRI methodology; farmers frequently report that intermittent irrigation or AWD water management is difficult to implement in many locations. Often this is given as a reason for limited adoption and/or for discontinuing SRI as in Indonesia (Takahashi, 2013), Cambodia (Ly et al., 2012) and Timor Leste (Noltze et al., 2012).

To a certain extent these problems can be solved by combining water-saving measures with engineering solutions, as well as by agronomic and soil management practices (Ali and Talukder, 2008). Water harvesting is one of the options which can improve agricultural productivity by collecting and conserving rainwater for supplemental irrigation and other beneficial uses. An Indian NGO, PRADAN, has demonstrated a low-cost, water-harvesting technology that it calls 'the 5% model' which encourages farmers to convert 5% of their rainfed paddy fields into catchment ponds to trap and store rainwater during the monsoon. This enables them to provide supplementary irrigation to their crop, which generally raises their income and food security (UNEP, 2012).

Similarly, a Multi-Purpose Farming (MPF) system developed with farmers in Cambodia that builds upon SRI productivity gains enables them to increase and sustain much greater productivity from their limited land resources by converting some of it from rice monoculture to diversified agriculture with pond culture as

Table 1
Details of experimental treatments.

Treatments for rice crop management	Symbols	Cropping system
Conventional rainfed rice Rice crop was grown with conventional methods; only rainwater was used, no supplemental irrigation	C-RF	Rice only
Rainfed SRI rice Rice crop was grown with SRI methods; only rainwater was used, no supplemental irrigation	S-RF	Rice only
SRI rice with supplemental irrigation from groundwater Rice crop was grown with SRI methods; no stagnant water was kept in the field (excess rainwater was drained off); supplemental irrigation was provided as and when required	S-IRR	Rice only
SRI rice with supplemental irrigation from stored run-off water Rice crop was grown with SRI methods; no stagnant water was kept in the field (excess rainwater was collected in the refuge); supplemental irrigation was provided from water conserved in the refuge as and when required	S-INT	Rice + Fish + Horticultural crops

the pivotal innovation supplemented by growing more vegetables and fruits (CEDAC, 2007).

SRI offers a relevant agronomic management option under unreliable rainfall conditions. Because of the substantially reduced seed rates farmers can stagger the planting of several small nurseries to have appropriately young seedlings available when conditions are favorable for transplanting. Also as SRI recommends use of single and young seedlings for transplanting, small nurseries take only short periods to produce seedlings (10–14 days) as compared with 30 or more days for conventional production. Earlier reports have shown that SRI plants have robust roots (Barison and Uphoff, 2011; Thakur et al., 2011) and are better able to tolerate both waterlogging and drought stresses. Drought risks can be mitigated by producing crops with deep and robust root systems, which can be achieved by drastically reducing plant populations. This is one of the essential elements of the SRI approach.

It is not clear, however, to what extent reduced plant density, as followed under SRI methodology, will have similar beneficial effects on crop performance under rainfed conditions; or how the provision of drainage and supplementary irrigation would affect grain yield of rainfed SRI; or further, how land and water productivity in paddy areas could be maximized by combining SRI methods as an agronomic strategy with diversification of cropping beyond rainfed rice production. Such a strategy, referred to here as integrated SRI (ISRI), includes constructing and operating a pond (refuge) within the rice paddy as an engineering solution, along with planting fruits and vegetables on the area around the pond.

This study is the first effort to evaluate under controlled conditions the synergies that could be involved between and among various practices of integrated farming systems that capitalize upon the potential productivity gains from SRI methodology. As such it might reveal some interesting implications for smallholder farmers' food security.

2. Materials and methods

2.1. Experiment details

2.1.1. Experimental site and treatments

The field experiment was repeated during two years (the rainy seasons of 2009/10 and 2010/11) at the Experimental Research Farm, Deras, Mendhasal, in Khurda district, Odisha, India (20° 30′ N, 87° 48′ 10″ E). The farm's soils (pH = 5.5) are classified as *Aeric Haplaquepts*, being sandy clay-loam in texture (63% sand, 16% silt, and 21% clay) with low soil organic carbon content (1.11%). The mineral content of the experimental field's soil was assessed as follows: total nitrogen (0.10%), available P (Olsen) (13 mg kg^{-1}), exchangeable K (0.26 cmol kg^{-1} soil), exchangeable Ca (4.7 cmol kg^{-1} soil), available S (19 mg kg^{-1}), Zn (13 mg kg^{-1}), and Fe (394 mg kg^{-1}).

The experiment was laid out as a complete randomized block design with four treatments and three replications. Each plot size was 350 m^2. To prevent sideways-seepage between plots, plastic sheets were installed in the bunds down to a depth of 50 cm. The treatments evaluated were two methods of rice crop establishment and management – conventional methods and SRI, with the latter having two different water management regimes as described and detailed in Table 1. In addition, in the fourth treatment there was a rainwater harvesting structure to enhance rice-field productivity by including aquaculture and horticulture within the farming operation. This is referred to here as 'Integrated SRI'.

- The first treatment, conventional rainfed rice (C-RF) considered as the control, simulating farmers' field conditions against which to assess possible agronomic and economic improvements.

  The other three treatments used SRI methods adapted to rainfed conditions, with introduction of variations in water management and in the farming system to assess the effects of these changes.
- The second treatment (S-RF) practiced the same water management as in the C-RF treatment in order to assess the impact of SRI practices – other than water management – on crop growth, physiological performance, and yield.
- The third treatment (S-IRR) had a drainage facility installed to keep these plots moist but neither saturated nor flooded during the vegetative stage following the recommendation for SRI.
- The fourth treatment (S-INT) combined both SRI water management and a diversified farming system, i.e., polyculture instead of monoculture. On the 350 m^2 plot areas for this treatment, rice was grown on an area of 270 m^2, and a small pond with a surface area of 35 m^2 was dug (10% of the total plot area) with a depth of 2 m. The remaining 45 m^2 of the 80 m^2 area was for the refuge's sloping bunds (the design of this treatment is shown in Fig. 1). In this treatment, the rice crop was grown similar to S-IRR, except that the source of irrigation was rainwater conserved in the refuge/pond. The stored water in the pond served as a refuge for growing fish, while its surrounding bunds were used for growing horticultural crops (details provided in Section 2.1.4).

2.1.2. Rice crop management

A medium-duration rice variety, *Surendra* (130–135 days) which normally yields 3.5–5.0 ton grain ha^{-1} (DRD, 2006), was planted on all of the plots for the four treatments in both years. Germinated seeds were sown in a nursery (18th July in 2009 and 15th

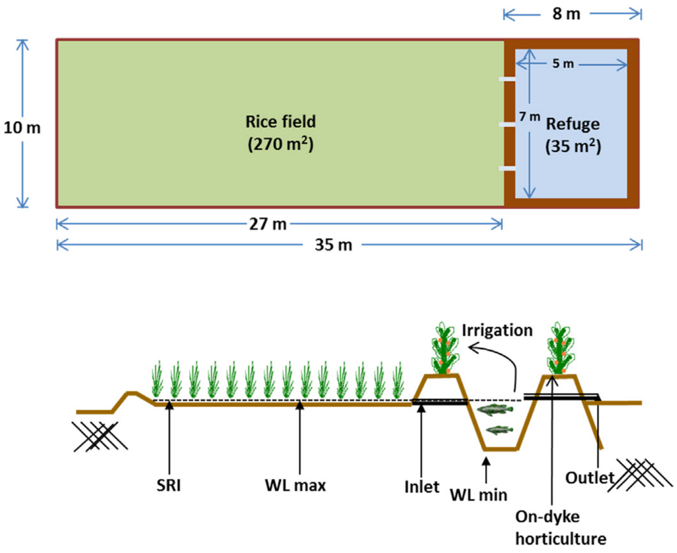

Fig. 1. Lay-out design of Integrated System of Rice Intensification.

July in 2010), and from there, 12-day-old single seedlings were transplanted for SRI plots at a spacing of 20 cm × 20 cm (25 plants m^{-2}) within 30 min after removal from the nursery. For the conventional method plots (C-RF), transplanting was done from the same nursery but after 25-days, using three seedlings $hill^{-1}$ at a spacing of 20 cm × 10 cm (150 plant m^{-2}), which is the common practice.

After completion of puddling, land leveling and draining off of excess water, fully decomposed cow dung manure (0.37% N, 0.19% P_2O_5 and 0.17% K_2O) was applied at the rate of 5 t ha^{-1} to all the experimental plots. Recommended doses of chemical fertilizers: urea (80 kg N ha^{-1}), single super phosphate (SSP) (40 kg P_2O_5 ha^{-1}), and muriate of potash (MOP) (40 kg K_2O ha^{-1}) were also applied to all the treatments. Full dose of P was applied at the time of final land preparation, while the N and K amendments were applied in three installments, i.e., 25% at 10 DAT, 50% at tillering stage (30 DAT), and 25% at panicle initiation stage (60 DAT). The usual recommendation for SRI is to rely on organic rather than chemical fertilization; however, in this experiment the fertilization regime was standardized across the four treatments, so as not to introduce another variable.

Weeding in SRI plots was done by using a mechanical conoweeder (http://www.ksnmconoweeder.com/) at 10, 20 and 30 days after transplanting (DAT), while conventional-method plots were weeded manually (by hand) three times at the same intervals. Rice was harvested from each plot on 30th November, 2009 in the first year, and on 28th November, 2010 in the second year.

2.1.3. Water management

Rainfall during the entire rice crop period (July-November) was 650.9 mm in 2009 and 1155.1 mm in 2010; daily rainfall data are presented in Fig. 2A and 2B. The 2009 wet season was considered as a 'drought' year, while 2010 was a 'normal' year. In the plots with conventional rainfed rice (C-RF) and rainfed SRI (S-RF), rice was cultivated exclusively with rainwater, whatever was the precipitation. The S-IRR and S-INT plots, on the other hand, were kept unflooded during the entire vegetative stage by draining off any excess rainwater. Moreover, supplemental irrigation from the pump or the pond was provided when there was no rainfall for a longer period. A total of 450 and 113 mm of water per ha was applied to the rice field from an external source in the S-IRR plots during 2009 and 2010, respectively. Similar amounts of water were applied in the S-INT plots, but this water was derived the refuge pond. After panicle initiation, a ponding depth of 2–3 cm was maintained on these plots until 15 days before harvest.

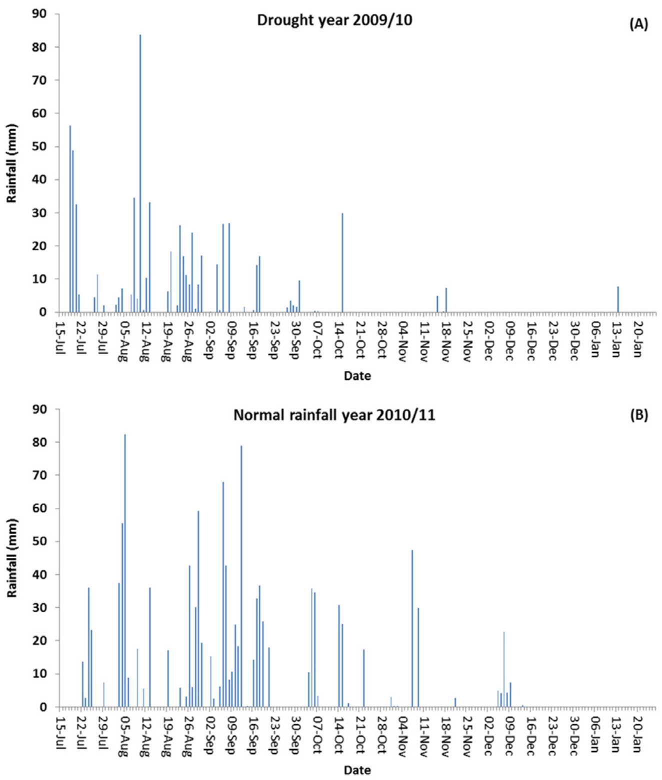

Fig. 2. Daily rainfall during experimental period (A) 2009/10 (drought) and (B) 2010/11 (normal rainfall).

2.1.4. Fish and horticultural crops management

In the treatment S-INT, short-duration fish culture of Indian major carps (IMCs) was undertaken, using harvested rainwater run-off from SRI fields in the adjacent refuges to enhance the economic output and water productivity. The pre-stocking preparation of the refuge included horizontal and longitudinal ploughing of the bottom followed by applications of lime ($CaCO_3$) at the rate of 750 kg ha^{-1}, raw cattle dung at 7000 kg ha^{-1} and fertilizer (urea and single super phosphate mixed in equal proportions at 3 ppm) as a basal dose (Mohanty et al., 2009).

Seven days after the refuge preparation, IMC fish fingerlings (*Catla catla*, *Labeo rohita* and *Catla mrigala*) were stocked @ 10,000 ha^{-1} with a stocking ratio of 30:30:40 (mean body weight = 34.8, 22.3 and 29.0 g for *Catla*, *Rohu* and *Mrigala*, respectively) in each refuge of 35 m^2 each. Artificial supplemental feed of mustard oil cake + rice bran (1:2) @ 3% of biomass was provided throughout the rearing period. The estimated crude protein of these feed ingredients was 8.8 and 37.3%, respectively, for the rice bran and mustard oil cake. Periodic manuring with raw cattle dung at 500 kg ha^{-1} and liming at 200 kg ha^{-1} were carried out at 15-day intervals to maintain the plankton population in the ecosystem. Fish were harvested at 150 days after stocking (23rd January, 2010 and 25th January, 2011).

Dwarf varieties of papaya and banana (15 each) were planted in the S-INT treatments during July 2009, alternately at a spacing of 2 m between plants on refuge bunds according to standard horticultural management practices. From July to January, these plants were irrigated with conserved refuge water. In the absence of water in the refuge from February to May, these were irrigated through groundwater, and the total water used during this period in two years (8 months total) was 9600 l.

2.2. Parameters measured

2.2.1. Water quality

Periodic observations on water quality parameters of both the irrigation and refuge water, such as dissolved oxygen (DO), temperature, pH, turbidity, total suspended solids, CO_2 and salinity, were monitored using standard methods (Mohanty et al., 2009). These parameters were crosschecked using a Multi-parameter Water Analyzer (YK-611, Yeo-Kal Electronics Pty. Ltd., Australia). The level of NH_4^+ was determined spectrophotometrically with the indophenol blue method, while chlorophyll-a was determined using the acetone extraction method (Strickland and Parsons, 1972). Primary productivity was analyzed using the 'Oxygen method' (APHA, 1995), while nutrient analysis followed standard methods (Biswas, 1993). Plankton samples were collected at fortnightly intervals by filtering 50 liters of water from each unit through a silk net (No. 25, mesh size 64 μm), preserved in 4% formaldehyde and later analyzed for quantitative and qualitative estimation

2.2.2. Plant height, tiller and leaf number

Five hills were randomly selected from each plot at the flowering stage for measurement of plant height, tiller and leaf number. Average number of tillers and leaves per hill was multiplied with the number of hills in unit area to calculate these parameters on an area basis.

2.2.3. Leaf area index (LAI) and light interception by the canopy (LIC)

During the flowering stage, the plants' leaf area was measured with a leaf area meter (LICOR-3100 Area Meter), and values for the leaf area index (LAI) were calculated by dividing the leaf area by the relevant land area. Light interception by the canopy (LIC) was calculated by measuring light intensity both above the canopy and at the surface of the soil under the canopy using a Line quantum sensor (400–700 nm) (Model: EMS 7; SW & WS Burrage, UK). The procedure used to measure LIC was reported in detail elsewhere (Thakur et al., 2011).

2.2.4. Determination of leaf chlorophyll fluorescence, photosynthesis rate, and chlorophyll content

Chlorophyll fluorescence is an indicator of light utilization capabilities of the leaves for light reaction of photosynthesis and CO_2 fixation. At the flowering stage, five flag leaves and the same number of fourth leaves (4th from the top) were marked in each plot for measurement of chlorophyll fluorescence – maximum quantum efficiency (Fv/Fm) and actual quantum efficiency (ΦPS II), with a Fluorescence Monitoring System (FMS-2, Hansatech). Leaves were dark-adapted for a period of 30 min using leaf clips prior to Fv/Fm measurements. Photosynthesis rate was measured from these same leaves with a CIRAS-2 Portable Photosynthesis System (PP Systems, U.K.). These measurements were similar to that used by Thakur et al. (2011). Chlorophyll content in leaves was determined by using the dimethyl sulfoxide (DMSO) method (Hiscox and Israelstam, 1979) and expressed in terms of $mg\,g^{-1}$ fresh leaf weight.

2.2.5. Root dry weight and xylem exudation rate

Five hills with an average number of panicles were randomly selected for root sampling from each plot at the early-ripening stage. Root samples were collected with the help of a spade by uprooting a hill up to a depth of 45 cm. Soil volumes sampled were 0.018 and 0.009 m^3 for SRI and conventional-method plots, respectively. The soil was carefully removed and the roots washed and dried in an oven at 65 °C until a constant dry weight was obtained, prior to recording root weight (Yoshida, 1981).

For measurement of the xylem exudation rate from detopped rice hills at the early-ripening stage, five hills were randomly selected from each plot with an average number of panicles. The procedure was similar to that used by San-oh et al. (2004) and Thakur et al. (2011).

2.2.6. Measurements of plant dry weight, yield, and yield components

The dry weight of plant samples was determined at harvest after oven-drying at 80 °C for 72 h to reach a constant weight. For determination of yield per unit area, all of the crops in a 5 m × 5 m area in the middle of each plot were harvested (excluding the border rows to avoid any border effect) for determination of yield per unit area after adjusting to 14.5% seed moisture content. Harvest Index (HI) was calculated by dividing dry grain yield by the total dry weight of aboveground parts. Plants harvested from a square meter area from each plot were used to determine average panicle number, panicle length, number of grains per panicle, and grain filling percentage.

2.2.7. Economic evaluation and water productivity

The ratio of the value of outputs (OV) to the cost of their cultivation (CC) was estimated for each of the four treatments. The depreciated annual cost of the excavated refuge construction which is a fixed cost, assuming a life span of 15 years, was added to the yearly variable cost of cultivation. The cost of the excavated refuge was Indian rupees (INR) 30 m^{-3} of soil. The operational cost included all the costs involved in rice cultivation, fish production, and growing horticultural crops.

The rate of water discharged through the pump and the irrigation time were multiplied to calculate the quantity of irrigation water applied. Economic indices of water productivity (net water productivity [NWP], in $INR\,m^{-3}$) were estimated as a ratio of net profit from the cultivation system and total water used (irrigation + rain).

2.3. Data analysis

The data were analyzed statistically by analysis of variance (ANOVA) technique (Gomez and Gomez, 1984) using SAS 9.2 (SAS Institute Inc., Cary, NC, USA). Apart from the treatments also the *year* and the *year* × *treatments* interaction effects were statistically analyzed. These effects were significant at $P < 0.05$ for some of the measured parameters, mainly because of the large difference in total rainfall and its distribution over the season between the two experimental years. Thus, the year effect is discussed as a factor affecting results. The rest of the data reported in this study are averages for the 2 years of trials. Duncan's multiple range test (DMRT) was employed to assess differences between the treatment means at the 5% probability level.

3. Results

3.1. Water quality in relation to crop production

The water quality in the refuge was compared with that of the pumped water used for irrigation in S-IRR plots. Conserved water from the refuge had significantly higher amounts of dissolved oxygen (DO), dissolved organic matter, total suspended solids (TSS), plankton, chlorophyll, and nitrogen; however the levels of phosphate, fluoride, and chloride were lower (Table 2). This might have had some effect on the crop productivity results.

Table 2
Variations in quality of conserved refuge water and irrigation water.

Water quality parameters	Conserved refuge water	Irrigation water
Water pH	7.3 ± 0.4	6.6 ± 0.3
Dissolved oxygen (mg L^{-1})	5.9 ± 1.3	4.1 ± 0.8
Temperature (°C)	28.4 ± 0.3	28.7 ± 0.6
Dissolved organic matter (mg L^{-1})	3.4 ± 0.4	1.6 ± 0.2
Total suspended solids (mg L^{-1})	265 ± 13	127 ± 17
NH_4^+ water (mg L^{-1})	0.68 ± 0.03	0.59 ± 0.03
Chlorophyll-a (mg m^{-3})	41.1 ± 3.2	9.3 ± 5.3
Total plankton (units L^{-1})	$33 \times 10^3 \pm 1.1$	$7 \times 10^2 \pm 1.4$
Nitrite – N (mg L^{-1})	0.06 ± 0.01	0.01 ± 0.00
Nitrate – N (mg L^{-1})	0.37 ± 0.06	0.16 ± 0.08
Phosphate – P (mg L^{-1})	0.21 ± 0.03	0.36 ± 0.04
Fluoride (mg L^{-1})	0.001 ± 0.0003	0.3 ± 0.1
Chloride (mg L^{-1})	0.01 ± 0.001	23 ± 2.6

All values are mean ± SD.

3.2. Effects on plant morphology (plant height, tillering, and leaf number)

At the flowering stage, clearly visible differences were observed in the morphological characteristics between different treatments. The rice crop grown with SRI methods was significantly taller than the crop grown under conventional flooded methods (Table 3). The tallest plants were grown under the S-INT treatments, being about 22% taller than C-RF.

SRI practice also significantly increased the number of tillers per hill compared with conventional flooded rice. SRI crops grown under unflooded conditions, but with supplementary irrigation (S-IRR and S-INT), had significantly higher numbers of tillers per hill than did rainfed SRI rice (S-RF); the number of tillers per unit area was lowest under S-RF.

In spite of significantly lower number of tillers per hill under C-RF, its tiller numbers in unit-area terms were comparable with other treatments mainly because of the greater number of C-RF hills per unit area. A similar trend was found with the number of leaves per hill and per unit area. SRI hills had nearly twice the number of leaves per hill than C-RF, but there were no significant differences in the total number of leaves per unit-area among C-RF, S-IRR and S-INT. The lowest number of leaves m^{-2} was found in S-RF plots.

3.3. Effects on leaf area index (LAI) and light interception by canopy (LIC)

Leaves' interception of incidental solar radiation and the leaf area index (LAI) are widely used parameters for crop growth analysis (Yoshida, 1981). Leaf area index was significantly higher in plots with SRI method of cultivation – in spite of their reduced plant populations – than for rice grown under conventional rainfed methods (Fig. 3A). The highest LAI was found under the S-INT treatment, followed by S-IRR and S-RF.

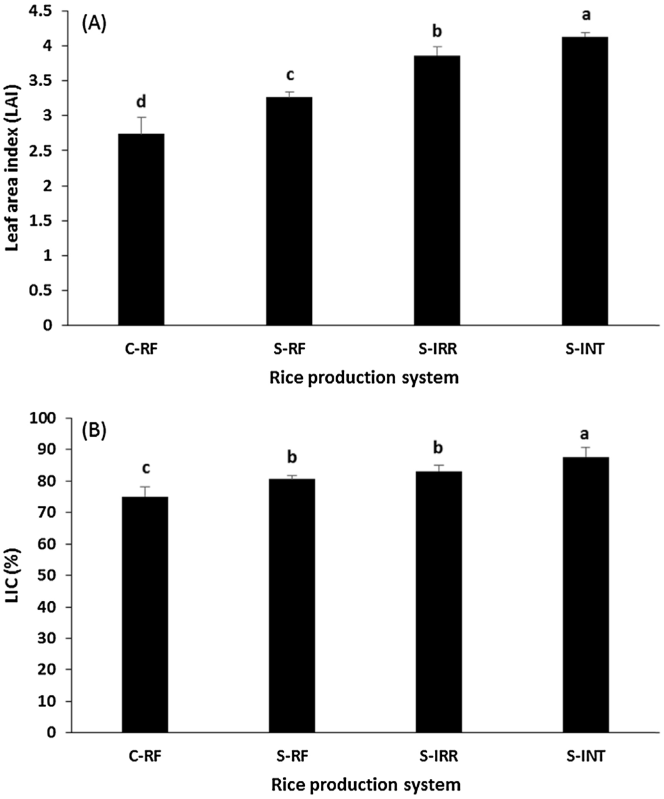

Fig. 3. Effects of rice production system on leaf area index (A) and light interception by canopy (B) at flowering stage of development. Vertical bars represent standard errors of the means ($n = 30$). Column with different letters denote significant ($P < 0.05$) difference between treatments by DMRT.

In spite of a comparable total number of leaves among the C-RF, S-IRR and S-INT treatments, the latter two treatments had higher LAI, mainly due to a significant increase in leaf size (both length and width). With an increase in LAI, the canopy of SRI rice crops also intercepted more light (7–16% more) compared to the C-RF crop. The highest light interception by the canopy (LIC) was observed in the S-INT treatment (Fig. 3B).

3.4. Effects on chlorophyll fluorescence, leaf chlorophyll content, and photosynthesis rate

Dark-adapted potential quantum yield (Fv/Fm) and actual quantum yield (ΦPS II) of leaves were measured at the flowering stage

Table 3
Effects of rice production system on morphological characteristics at flowering stage of development.

Rice production system	Plant height (cm)	Tiller number		Leaf number	
		($hill^{-1}$)	(m^{-2})	($hill^{-1}$)	(m^{-2})
C-RF	99.1 d	9.8 c	490.8 a	40.7 d	2033.3 a
S-RF	110.1 c	16.2 b	404.6 b	71.0 c	1775.0 b
S-IRR	116.7 b	18.4 a	460.8 a	81.3 b	2033.3 a
S-INT	121.3 a	19.2 a	480.0 a	87.0 a	2175.0 a
Analysis of variance					
Year (Y)	ns	ns	ns	ns	ns
Treatment (T)	*	**	*	**	*
Y × T	ns	ns	ns	ns	ns

Mean values followed by different letters denote significant ($P < 0.05$) difference between treatments by Duncan's range test.
ns: not significant.
[*] Significant at $P < 0.05$.
[**] Significant at $P < 0.01$.

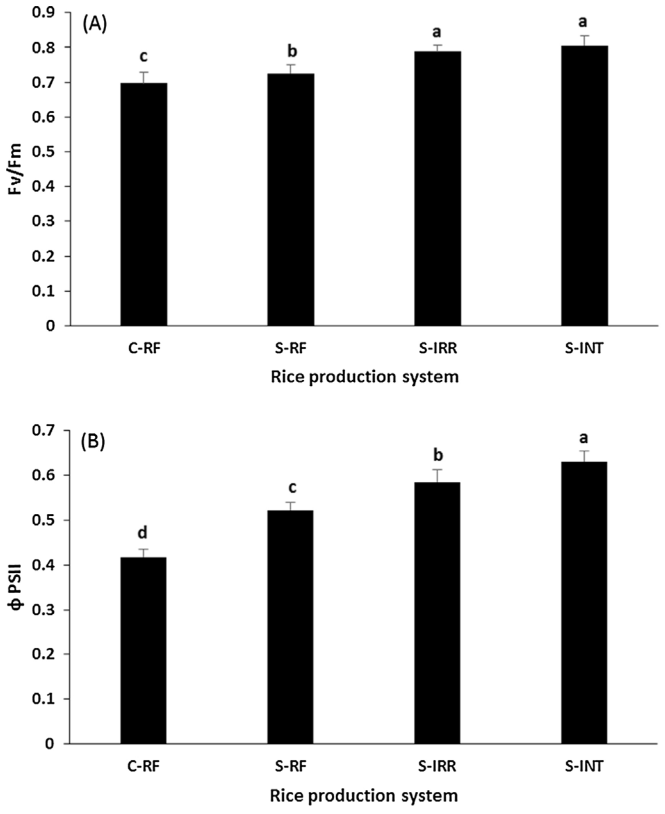

Fig. 4. Effects of rice production system on chlorophyll fluorescence potential quantum yield – Fv/Fm (A) and actual quantum yield – ΦPS II (B) at flowering stage of development. Vertical bars represent standard errors of the means ($n = 30$). Column with different letters denote significant ($P < 0.05$) difference between treatments by DMRT.

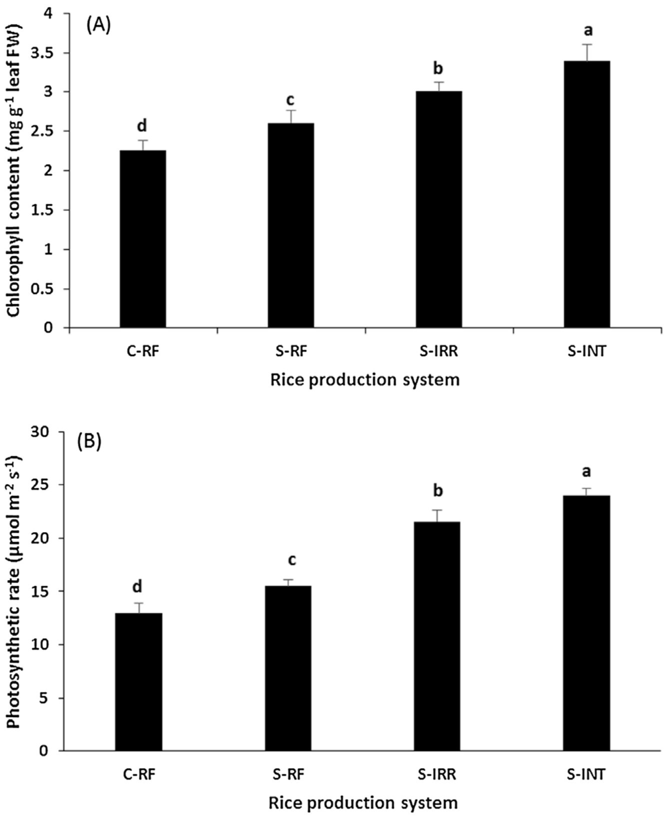

Fig. 5. Effects of rice production system on leaf chlorophyll content (A) and photosynthesis rate (B) at flowering stage of development. Vertical bars represent standard errors of the means ($n = 30$). Column with different letters denote significant ($P < 0.05$) difference between treatments by DMRT.

to understand whether different rice production systems have any impact on light utilization by the crop during photosynthesis. At flowering stage both of these parameters (Fv/Fm and ΦPS II) were significantly greater in plants grown under SRI practice as compared with the conventional method (Fig. 4A and B). Among the different SRI treatments, these two parameters were highest for plants grown under S-INT.

This indicates that the plants grown with S-INT method had significantly greater maximum and actual quantum efficiency than did the plants grown under other cultivation methods. Leaves of plants grown under S-INT also had significantly higher chlorophyll contents (Fig. 5A) than those of leaves for the C-RF treatment, which is likely to be associated with photosynthesis rates that were nearly double in the former (see Fig. 5B).

3.5. *Effects on root growth and activity*

At the early-ripening stage, root growth and root activity were seen to be significantly affected by crop and water management practices. Rice plants grown with SRI practices had two to three times greater root dry weight per hill as well as more amount of exudates per hill transported from roots toward shoots as compared with rice grown under conventional rainfed management practices (Table 4). Not surprisingly the increase in root mass/weight is linked to higher rates and quantities of xylem exudates (Table 4) which ultimately led to a highly significant response in grain yields (see Sections 3.6 and 3.7).

The data indicated a significantly better root growth and performance (as recorded during the early-ripening stage of the crop) under SRI treatments than for the conventional method. As mentioned above, the highest root dry weight and amount of xylem exudates among the different SRI management systems was recorded when the rice was grown with no standing water on the field and with the supplementary irrigation provided from conserved refuge water (S-INT).

3.6. *Effects on yield contributing-characteristics and harvest index*

Average panicle number per hill was significantly increased (double) under rainfed SRI as compared with the conventional method (Table 5), and further increased under the S-IRR and

Table 4
Effects of rice production system on root growth and activity at early-ripening stage of development.

Rice production system	Root dry weight (g)		Amount of exudates (g)	
	(hill⁻¹)	(m⁻²)	(hill⁻¹)	(m⁻²)
C-RF[1]	4.1 d	206.3 c	2.26 d	113.2 d
S-RF[2]	7.5 c	187.0 d	5.38 c	134.6 c
S-IRR[2]	10.2 b	254.3 b	7.19 b	179.8 b
S-INT[2]	12.3 a	308.0 a	7.82 a	195.4 a
Analysis of variance				
Year (Y)	ns	ns	ns	ns
Treatment (T)	**	**	**	**
Y × T	ns	ns	ns	ns

Mean values followed by different letters denote significant ($P < 0.05$) difference between treatments by Duncan's range test.
ns: not significant.
** Significant at $P < 0.01$.
[1] Conventional method refers to 3 plants hill^{-1} and 150 plants m^{-2}.
[2] SRI refers to 1 plants hill^{-1} and 25 plants m^{-2}.

Table 5
Effects of rice production systems on yield-contributing characteristics, straw yield and harvest index (HI).

Rice production system	Ave. panicle number hill^{-1}	Panicles (m^{-2})	Ave. panicle length (cm)	Spikelet number/panicle	Filled spikelets (%)	1000-grain weight (g)	Straw yield (t ha^{-1})	Harvest index
C-RF	6.4 c	321.7 b	14.6 d	99.8 d	75.5 b	22.9 b	5.00 c	0.36 c
S-RF	13.2 b	328.8 b	18.2 c	119.5 c	74.9 b	24.3 a	6.38 b	0.41 b
S-IRR	16.8 a	420.2 a	20.9 b	130.5 b	86.4 a	24.4 a	6.59 ab	0.46 a
S-INT	17.2 a	428.8 a	22.0 a	146.9 a	86.5 a	24.4 a	6.81 a	0.47 a
Analysis of variance								
Year (Y)	ns	ns	ns	ns	*	ns	*	ns
Treatment (T)	**	*	*	**	**	*	**	*
Y × T	ns	ns	ns	*	**	*	*	*

Mean values followed by different letters denote significant ($P < 0.05$) difference between treatments by Duncan's range test.
ns: not significant.
* Significant at $P < 0.05$.
** Significant at $P < 0.01$.

S-INT treatments. Panicle number per unit area was similar under both conventional and SRI rainfed system; however, it was significantly greater in the S-IRR and S-INT systems than in the C-RF and S-RF systems. Average panicle length under conventional rainfed method was 14.6 cm, which was significantly lower than the 18.2–22 cm recorded under SRI methods. Similar trends were recorded for other yield-contributing parameters like spikelet number panicle^{-1}, grain filling %, and 1000-grain weight. The significantly higher harvest index (HI) also supports the proposition that SRI methods greatly increased the efficiency of rice plants in producing grain.

Parameters like grain-filling, grain weight, straw yield, and harvest index were all significantly influenced by *year* and/or by *year* × *treatment* interactions. These effects were caused because during the first year (2009, characterized as a drought year), there was almost no rain after 15th of October, i.e., during the middle period of the crop's reproductive stage. These unfavorable weather conditions during ripening hampered growth and grain development relatively more in the conventional system than in the various SRI treatments.

3.7. Effects on grain yield

Apart from the system treatments, the *year* and *year* × *treatment* interactions all had highly significant impacts on grain yields. The highest rice grain yield was recorded in the S-INT treatments, followed by S-IRR and S-RF (Table 6). The lowest rice yield was recorded for conventionally grown rainfed rice (C-RF).

The percentage increases in grain yield from the S-RF, S-IRR and S-INT treatments over the conventional method were, respectively, 52, 97 and 113%. It was further noted that a 52% yield enhancement in S-RF compared to C-RF was due to differences in the method of rice cultivation, notably as a result of using younger seedlings and greatly reduced plant density. This resulted in significant improvements in morpho-physiological characteristics and in yield-contributing characteristics.

Table 6
Effect of rice production systems on grain yield during 2009 and 2010 *kharif* (wet) season.

Rice production system	Grain yield (t ha^{-1})		
	2009	2010	Mean
C-RF	2.36 g	3.41 f	2.89 d
S-RF	4.21 e	4.61 d	4.41 c
S-IRR	5.96 b	5.43 c	5.70 b
S-INT	6.22 a	6.09 b	6.16 a
Analysis of variance			
Year (Y)			*
Treatment (T)			**
Y × T			**

Mean values followed by different letters denote significant ($P < 0.05$) difference between treatments by Duncan's range test.
* Significant at $P < 0.05$.
** Significant at $P < 0.01$.

Concurrently, improvements in grain yield in S-IRR compared to S-RF were found to be 29%, mainly due to the supplementary irrigation from groundwater pumping. The further yield improvement of an additional 16% from S-INT plots compared to S-IRR plots was due to irrigating the former with stored refuge water rather than with groundwater, and this mainly reflects differences in water quality as the quantities of water applied were essentially the same between S-IRR and S-INT (Section 3.1).

Further, during the 2009 drought year, grain yield enhancements in S-RF, S-IRR and S-INT as compared with conventional rainfed rice were increased by 78%, 152% and 163%, respectively (Fig. 6). During a normal rainfall year (2010), the grain yield enhancements in S-RF, S-IRR and S-INT compared with conventional treatment were less than in the drought year, i.e., 35%, 59% and 78%, respectively. The yield advantage of the SRI treatments in a drought year was about double the advantage in a 'normal' year, although in the latter it still averaged more than 50%. Interestingly, the grain yield increases from SRI practices were relatively little affected by the unfavorable 2009 rainfall distribution (Table 6).

3.8. Effects of plant density on below- and above ground development for individual plants

An important aspect to notice is that plant root weight, which in the conventional system (C-RF) with 150 plants/m^2 was 1.4 g/plant, increased to 7.5 g/plant – nearly 5 times more – for the SRI rainfed treatment with 25 plants/m^2 (Table 7). For SRI with supplementary irrigation, this root weight increased further to 10.2 g/plant in

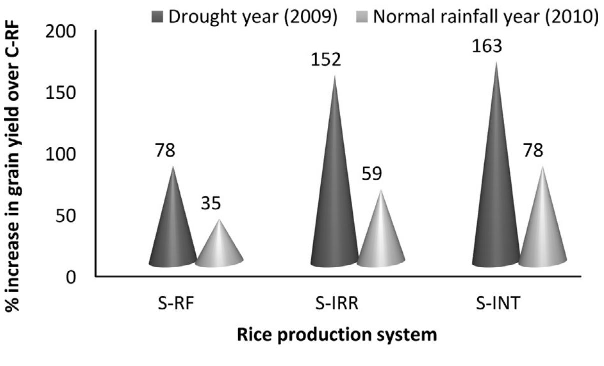

Fig. 6. Grain yield increases (%) in various SRI systems over the conventional rainfed (C-RF) rice system for a drought year (2009) and a normal rainfall year (2010).

Table 7
Effects of plant density on below- and above ground development for individual plants under rice production systems.

Rice production system	No. of plants m^{-2}	Root dry weight[a] (g $plant^{-1}$)	Straw weight[a] (g $plant^{-1}$)	Grain yield[a] (g $plant^{-1}$)
C-RF	150	1.4	3.3	1.9
S-RF	25	7.5	25.5	17.6
S-IRR	25	10.2	26.4	22.8
S-INT	25	12.3	27.2	24.6

[a] Calculated values; root dry weight per plant were calculated by root dry weight m^{-2} divided by number of plants in unit square meter area. Similarly straw weight and grain yield per plant were calculated.

S-IRR, and to 12.3 g/plant in S-INT, a tenfold increase in root mass as compared with the plants in the conventional system.

The six-fold reduction in plant density under SRI as compared with conventional management resulted in 7–8 times more straw production/plant and produced 9–12 times more grains/plant (Table 7). This result illustrates that the drastic reduction in plant density (as associated with SRI) was positively compensated for by the increased plant growth (both below and above ground), which ultimately translated into substantial grain yield increases.

3.9. Fish production, fruit yield, economic evaluation, and water productivity

A fish harvest was made in both years from the S-INT plots in January, after 150 days of rearing. The average mean body weight (MBW) for the three varieties of carp being raised from the two harvests was 346.9, 265.8 and 274.5 g for *Catla*, *Rohu* and *Mrigal*, respectively. Fish yield from the 35 m^2 area of refuge during 2010 and 2011 was 9.3 and 9.1 kg, respectively, amounting to an average yield of 2.6 t ha^{-1}.

Also from the S-INT plots, an average total of 1050 kg of papaya and 30 bunches of bananas were harvested in the two years from the bund areas of 45 m^2 of each refuge (from 15 trees each), with an average of 70 kg per papaya plant and 2 bunches of bananas per plant. With a selling price of Rs. 6 kg^{-1} for papaya and Rs. 125 for each bunch of bananas, the total income received in the two years was Rs. 10,050 from the bund area of each S-INT refuge.

Net profit from the integrated system (including rice, fish and horticultural crops) was significantly higher than from the other three systems (Table 8). The conventional rice system had a net profit of only Rs. 153 for two years from an area of 350 m^2, equivalent to Rs. 4371 ha^{-1} in the two years. Concurrently, the integrated system with a similar area and same climatic conditions during the two years produced a net profit of Rs. 9401, equivalent to Rs. 268,600 ha^{-1} total net profit over two years.

The output value over cultivation costs ratio (OV:CC) indicated that in the Integrated SRI system, an investment of Rs. 1, yields a return of Rs. 2.97 (almost three times), while the conventional upland paddy cultivation, on the other hand, was not much more than a break-even operation (OV:CC = 1.13). The net water productivity (NWP) in the Integrated SRI system was calculated to be Rs. 18.91 m^{-3} of water (S-INT), while it was only Rs. 0.31 m^{-3} of water in the conventional rice cultivation system. This indicates a significant economic gain per volume of water for the integrated system (Table 8).

4. Discussion

Enhancing actual cereal yields has been identified as one of the main challenges to secure food supply to an increasing global population (Godfray et al., 2010; Normile, 2008). The challenge is, however, that greater food production must be achieved in the coming years under water-scarce and changing-climate conditions (Gornall et al., 2010; Meinke et al., 2009; Naylor et al., 2007).

In recent years, the System of Rice Intensification (SRI) has generated considerable interest among farmers, researchers, NGOs, print media, and governments. SRI was developed initially for irrigated conditions, and most of the evaluations have been done for that situation (Kassam et al., 2011). Much rice, however, is grown under rainfed conditions and without irrigation facilities. This situation poses a number of highly relevant questions with respect to the various SRI practices: (a) whether its practices, especially the low plant densities, have any significant effect, positive or negative, on grain yield when facilities for controlled irrigation are absent, and when the crop is subjected to the vagaries of adverse weather under rainfed conditions, (b) how much better could SRI practices under rainfed conditions perform if facilities for supplementary irrigation and drainage are installed to compensate for varying climate effects, (c) what options are there to collect, store and utilize the rainwater that falls during the rainy season to enhance land and water productivity, and (d) what are the magnitudes of effects on net income from this stored water if used also for aquaculture and horticulture along with rice production.

Rainfall distribution during the *kharif* season is always relatively unpredictable, as illustrated in Fig. 2 for the two years of experimentation. This implies that the recorded crop and yield response data will vary considerably from year-to-year. The present results provide valuable information as to how year-to-year fluctuations in the yields of rice and other crops, caused by varying rainfall patterns, might be minimized, and they show the critical role that is played in this by having more profuse and better-functioning root systems.

Table 8
Economic analysis of different rice production systems (combined values from 2 years of experimental results).

Rice production system[a]	Cost of cultivation (CC) (INR)	Output value (OV)[c] (INR)	Net profit (INR)	OV:CC ratio	Water used (m^3)	Net water productivity (INR m^{-3})
C-RF	1183.0	1336.0	153.0	1.13	487.6	0.31
S-RF	1155.0	2468.7	1313.7	2.14	487.6	2.69
S-IRR	1355.0	3189.2	1834.2	2.35	661.5	2.77
S-INT[b]	4782.1	14183.0	9401.0	2.97	497.2	18.91

Indian rupees (INR) 61.5 = 1 USD.

[a] Area of the each replicated plots was 350 m^2.

[b] In S-INT system, out of the 350 m^2 area – 270 m^2 was used for rice cultivation, 35 m^2 was the refuge area used for fish culture, and the remaining 45 m^2 bund area was used for horticultural crops.

[c] Selling prices of rice and fish were Rs. 8 and Rs. 80, respectively. Selling prices of papaya and banana were Rs. 6 kg^{-1} and Rs. 125 $bunch^{-1}$, respectively.

4.1. Bio-technical aspects of SRI

By now, many studies have confirmed SRI's yield gains in the order of more than 50% (Kassam et al., 2011; Sinha and Talati, 2007; Thakur et al., 2010a, 2010b; Uphoff, 2007; Zhao et al., 2010), while reducing crop water requirements (Chapagain and Yamaji, 2010; Ndiiri et al., 2013; Satyanarayana et al., 2007; Thakur et al., 2011; Zhao et al., 2010). Earlier, researchers have shown that respective individual SRI practices are responsible for yield increases under irrigated rice cultivation, e.g., the use of single seedlings (San-oh et al., 2004, 2006), young seedlings (Pasuquin et al., 2008), and wide spacing (Thakur et al., 2010a).

In the present experiment it was seen that as compared to the conventional system (C-RF), the S-RF system introduced several important modifications: wider hill spacing and one transplanted seedling per hill (leading to a drastic reduction in plant densities), use of young seedlings for transplanting, and utilization of a soil-aerating mechanical weeder. These practices contributed to the development of more profuse and active root systems, and this combination of SRI practices was able to enhance rice production by >50% under rainfed conditions. Conventional rainfed rice fields, by contrast, are populated by masses of inefficiently functioning individual plants as a result of excessive inter-plant competition, resulting also in suboptimal utilization of applied fertilizers (Thakur et al., 2013).

The research here showed that SRI practices, even under rainfed conditions provided a better growing environment for rice plants which had significantly more roots, tillers and leaves. At the flowering stage, rainfed SRI plants showed significant improvement in their morphology, with significant increases in plant height, tillering, and leaf size (Table 3), also the leaf area index responsible for greater light interception was increased (Fig. 3). Concurrently, the SRI practices (S-RF) contributed to improved root growth and functioning (Table 4) and to increases in leaf chlorophyll contents, fluorescence efficiency, and photosynthetic rates (Figs. 4 and 5).

A 6-fold reduction in plant density under SRI resulted in a 5–9 fold increase in root growth per plant explaining the greater nutrient and water use efficiency (Table 7). This was then accompanied by substantial increases in grain yield. This is in turn explained by an increase in straw (reflecting photosynthetic activity) and the greater translocation of carbohydrates/photosynthates from the foliage to the grain as reflected also by the increases in grain size (1000 grain weight) and HI. These results complement earlier ones for irrigated SRI (Thakur et al., 2013) where the highest grain yield ($6\,\mathrm{t\,ha^{-1}}$) was obtained at a moderate rate of nitrogen fertilizer (of $90\,\mathrm{kg\,N\,ha^{-1}}$) with greater N-uptake and use efficiency, affected profoundly by the extensiveness of root systems.

In other previous work on irrigated SRI management, we reported that improvements in the basic morphological characteristics of rice plants contributed to better physiological functioning, that translated directly into an increase in grain yield (Thakur et al., 2010b, 2011). It is interesting to note that in the S-IRR and S-INT treatments, a further improvement in grain yield was recorded when excess rainwater was drained from the field (so there was no stagnant water) and supplemental irrigation was provided on an as-needed basis.

Earlier, Zhang et al. (2009) similarly concluded that keeping the paddy field unflooded and following an irrigation regime of moderate wetting and drying significantly increased root growth and root oxidation activity. This benefits physiological processes like cytokinin concentrations in the roots and shoots, the leaves' photosynthetic rate, and the activities of key enzymes involved in the sucrose-to-starch conversion in grains. These are all fundamental processes that are ultimately reflected in grain yield.

4.2. SRI practices under risk situations: a new possibility

Adopting any water-saving methodology for rice production including the irrigation method recommended for SRI (keeping fields unflooded) is quite difficult during the wet season in certain regions of most countries in South and South-east Asia. Substantial amounts of rainfall may occur over a few months, but there can also be prolonged dry spells. Under these situations, a rice crop faces the problems of having either too much water that suffocates roots and/or moisture stress. Ultimately, either or both result in serious yield losses in particular when the plants did not develop a deep and healthy root system during their initial growth stages.

Drastically reducing the number of plants per unit area is one of the major practices followed under SRI method (Stoop et al., 2002). In the present study, reducing plant densities six-fold under SRI (to 25 instead of 150 plants $\mathrm{m^{-2}}$) was positively compensated for by increased plant growth (both root and shoot) and increased grain yield. In the context of achieving/improving yield stability to cope with the weather and rainfall fluctuations associated with climate change, this is an important result, particularly so – although not exclusively – for the multitude of smallholder farmers operating in developing countries (Morton, 2007).

During the drought year (2009), the reduction in grain yield with conventional rainfed cropping was considerable (2.36 vs $3.41\,\mathrm{t\,ha^{-1}}$), whereas under rainfed SRI methods it was slight (4.21 vs $4.61\,\mathrm{t\,ha^{-1}}$). Supplementary irrigation (both S-IRR and S-INT) was able to raise the grain yield to similar levels of about 6 ton/ha in both years (Table 6). This clearly indicated that crops grown with SRI methods are less sensitive to drought than are the crops under conventional rainfed system. SRI plants were more drought-tolerant, mainly due to their greater and more robust root systems. Reduced plant densities, as followed under SRI, seem to be a simple means to alleviate the risks of unreliable rainfall. To be sure, sparsity is a factor to be optimized, rather than maximized. Unfortunately for farmers, most research to date has sought to optimize crowding and therefore has evaluated plant/crop performance in terms of what is the most productive stunting rather than in terms of what is the best growth.

According to Berkhout et al. (2015), water savings and improvements in water productivity can be achieved by adopting water-saving management methods, without necessarily adopting the whole set of SRI practices. The present study confirms that it is indeed not necessary to adopt the whole set of SRI practices to enhance productivity. In the present case of rainfed SRI (S-RF), grain yield and water productivity were already improved significantly by adopting just some of the recommended SRI practices (particularly the wide spacing/low plant density and young seedlings).

It should be notes, however, that this study did not evaluate the contribution that two additional recommended SRI practices that could add to farming system productivity: increasing organic-nutrient applications to further improve soil structure and functioning, and active soil aeration through a mechanical weeder adapted to unflooded soils. The effects of these practices in conjunction with the SRI practices studied here will require similar kinds of scientific investigations and evaluation.

4.3. Integrated SRI: potential for improving water productivity and food security for smallholders

The challenge of enhancing water productivity in agricultural production can be met by producing more output per unit of water used, or by reducing water losses, or by a combination of both. A number of possible ways to improve water productivity in crop production have been identified by researchers (Ali and Talukder, 2008; Bouman, 2007; Nangia et al., 2008; Sandhu et al., 2012); the use of water-saving irrigation methods is widely considered the most important one. Methods, like alternate wetting-and-drying (AWD) or saturated soil culture or intermittent irrigation, are important management measures to reduce water losses from irrigated rice fields. Generally, these methods – while enhancing water productivity – achieve this, however, at the expense of a reduced grain production (Bouman and Tuong, 2001; Tuong and Bouman, 2003; Tuong et al., 2005).

Villages in India, Sri Lanka and other Asian countries have harvested rainwater for supplementary irrigation since ancient times by directing surface runoff into reservoirs or on-farm ponds or cisterns (Brohier, 1934; Falkenmark and Rockström, 2004). Seepage and drainage water is quite often collected in small ponds, ditches, drains and canals from where it can be reused by pumping (Bouman, 2007). For example, in Zanghe Irrigation System in Hubei, China, thousands of on-farm and village-level ponds were constructed to capture drainage/run-off water from rice fields (Mushtaq et al., 2006). Oweis and Hachum (2006) have demonstrated that water harvesting and supplemental irrigation can improve water productivity in dry-farming systems in West Asia and North Africa. Dugan et al. (2006) also demonstrated that substantial benefits and higher water productivity can be obtained by combining intensive aquaculture with irrigated crop production. Likewise, Khumairoh et al. (2012) in East Java (Indonesia) show that the irrigated SRI rice production system can result in increased grain yields and additional revenues by adding different combinations of compost, azolla, ducks, and fish, documenting synergies among these components of the farming system.

With the integrated SRI methods investigated here, runoff water was harvested/saved in a small refuge and used for need-based supplementary irrigation for the rice crop and also for maintaining aquaculture and for irrigating horticultural crops. Also important, the pond water became nutrient-rich as reflected by the water-quality parameters presented in Table 2. By using this nutrient-rich pond water, instead of pumped groundwater, for irrigating the adjacent rice plot, the grain yield was increased by an additional 8% (Table 6). Additional income was generated from fish culture in the small pond and from the horticultural crops grown on the bunds. In this way, net water productivity was multiplied more than 60-fold, from Rs. 0.31 m^{-3} in the conventional rainfed system (C-RF) to Rs 18.91 m^{-3} in the integrated (S-INT) system (Table 7).

This study has demonstrated that the use of SRI practices, which by themselves can produce more grain, can further improve the productivity of farming systems' resources while practicing it in conjunction with aquaculture and horticulture. Very high levels of productivity can thus be attained from a small land area provided that its associated water resources are captured and utilized. This method appears to have much potential to enhance food security and livelihoods for smallholder households by managing available water for both rice and fish along with horticultural crops, while managing the rice crop itself differently.

5. Conclusion

The results of the field investigation reported here revealed that SRI practices adapted to rainfed conditions can significantly improve rice grain yields, but also overall resource productivity. This improvement can be attributed to an increased efficiency in the plants' physiological performance that has resulted from morphological changes in several key characteristics of rice plants as compared with conventional cultivation methods for rainfed rice. This study demonstrated that – mainly as a result of substantially reduced plant densities – rice plants developed profuse and robust root systems in support of above-ground development and an increased grain yield. This effect was enhanced further, particularly in drought years, by providing supplementary irrigation.

Under the risky conditions of rainfed cultivation, SRI practices provide new possibilities for food security and poverty reduction as seen by their consistently outperforming conventional practices. Harvesting excess rain water and storing it within the rice field in a constructed pond or refuge provides farmers with options for integrating aquaculture with rice cultivation and also for growing horticultural crops on the refuge bunds. This significantly improves water productivity and therefore offers smallholders an option to enhance their income while improving their food security and livelihoods.

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