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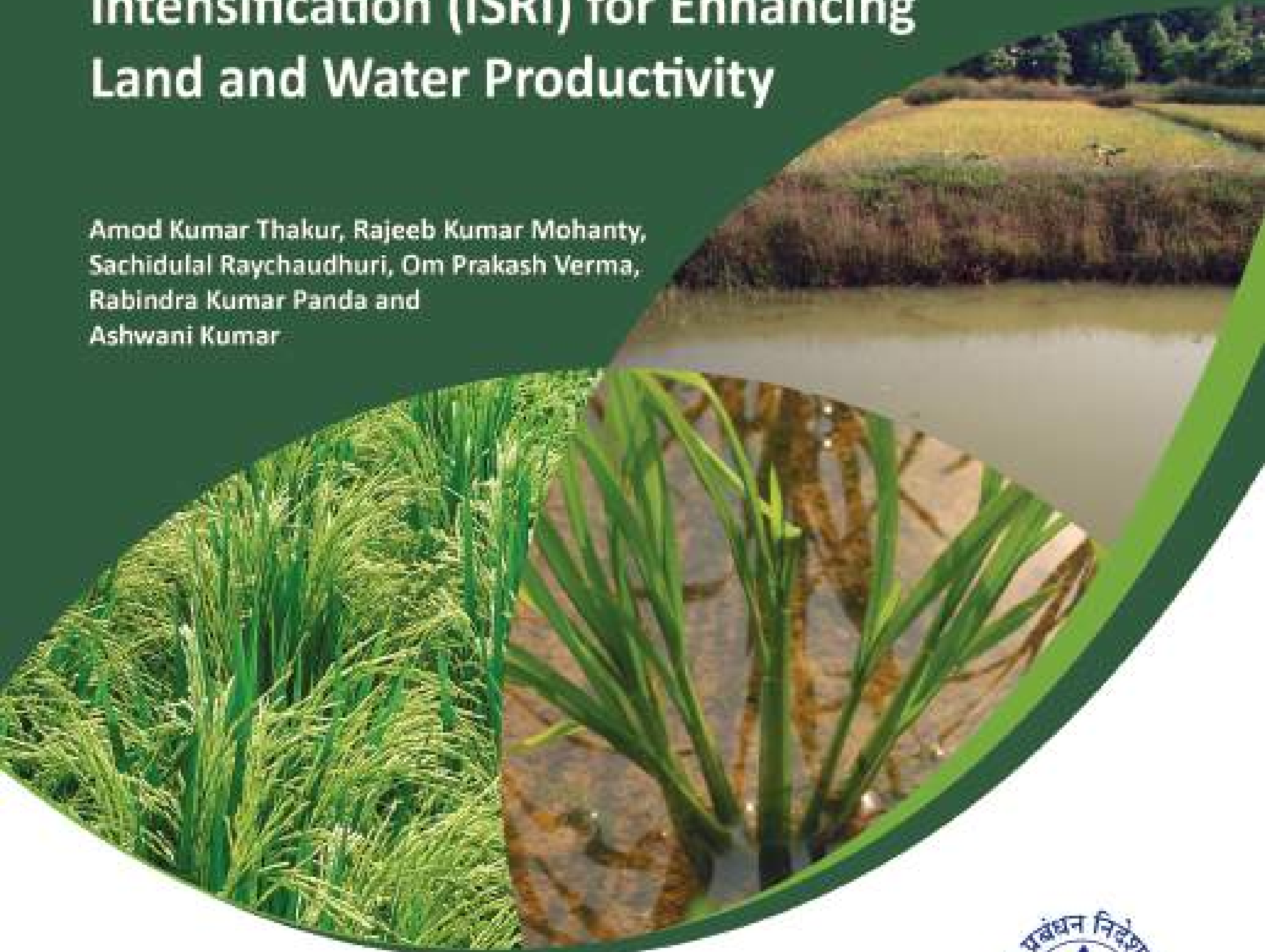

Directorate of Water Management
(Indian Council of Agricultural Research)
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Contents

Preface

Today growing enough food to feed 9 billion people by 2050, with limited land, water and nutrient resources under changing climate is a major challenge in agriculture. Rice is the staple food for more than 3 billion people in the world, making it the most important food crop for human consumption and food security. To fulfill needs of the growing population, global average rice yield needs to be increased by 12% over the yield level of 2005 by 2015. Greatest challenge for rice farming is water scarcity and erratic rainfall pattern. Given that rice is a dietary staple for half the world with annual production of 463 mt in 2011, then 1.2×10^{15} liters of water is required for rice production globally.

In rice cultivation, generally paddy fields are kept continuously submerged. In rainfed areas, which amount to 54 million ha worldwide, rainfall is the only source of water to the field. In most of these areas, rice is grown only in the rainy season, and most of the rainwater is lost from rice fields either by evaporation or by seepage and percolation that can cause groundwater contamination and environmental pollution. High costs of production, low productivity (both crop and water), and poor fertilizer use-efficiency are common features of rainfed rice. Also, major problem in these areas is first to control excess water when there is heavy downpour and to keep it from harming standing crops; and second, there is need to manage drought stresses when there is not sufficient rain. It is quite difficult to adopt any water-saving irrigation methods in rice cultivation in these areas during rainy season.

System of rice intensification (SRI), a new method of rice cultivation have been reported enhance productivity with less water and incorporates water-saving irrigation method, which is very difficult to implement during rainy season.

A team of scientists from Directorate of Water Management (ICAR), Bhubaneswar, conducted research with a objective to enhance both land and water productivity through adopting SRI method of rice cultivation along with a water harvesting structure to save excess rainwater- to use for growing short-term pisciculture, horticultural crops and for providing supplementary irrigation to rice crop. Salient findings of their experiments are included in this bulletin.

Authors are grateful to Director General of ICAR, Deputy Director General and Assistant Director General of Natural Resources Management Division of the ICAR, New Delhi for their valuable support, suggestions and encouragement in carrying out this research under in-house projects. We sincerely thank all colleagues and staff members of this institute for their help, cooperation and encouragement. We hope that this research bulletin will be very useful to the researchers, stake holders/ development agencies, water resources departments, farmers and to all those who will be interested for the management of water to enhance productivity.

- Authors

Executive Summary

Enhancing food crop production under increasing water constraints and greater climatic variability challenges us to improve both land and water productivity. In many areas, where substantial rainfall occurs over a few months and rice cultivation is dependent upon only rainwater faces either heavy rainfall or long dry spells, often results in low productivity and environmental pollution. A 2-year field experiment was conducted with an aim of enhancing the economic productivity of land and water under rainfed conditions, where mostly only a rainy-season rice crop can be grown. Four possible rice cultivation systems were evaluated: (i) conventional rice cultivation methods under rainfed conditions, (ii) System of Rice Intensification (SRI) methods adapted to rainfed conditions, (iii) rainfed SRI methods with drainage and supplementary irrigation to ascertain what these facilities could add, and (iv) SRI methods utilizing rainwater harvesting to collect excess rainwater and store it for utilizing aquaculture and horticulture crops also with a provision of supplementary irrigation for rice crop.

Changes in rainfed rice cultivation through adaptations of SRI practices increased grain yield by 53% compared with conventional rice production method. Significant improvements were observed in the morphology and physiology of rice plants grown with adapted SRI practices. Phenotypic improvements included: greater xylem exudation rate, higher light interception by the canopy, and more chlorophyll content, greater light utilization, and higher photosynthetic rates in the leaves during the flowering stage. These changes were responsible for the improvement in yield-contributing characteristics and the higher grain yield compared with conventional production methods.

Drainage and supplementary irrigation as expected improved both grain yield and water productivity for rainfed SRI. Further, integrating aquaculture and horticulture with SRI management, plus having harvested rainwater available in an in-field refuge, increased rice productivity and enhanced net water productivity. This raised net income per unit of water substantially compared with conventional rice cultivation.

Combining SRI rice cultivation with aquaculture and horticulture, harvesting rainwater and providing some supplementary irrigation, looks promising for improving food security under future conditions of water scarcity and climate change. This farming systems innovation could be especially important for disadvantaged, food-insecure households living and cultivating under less-favorable circumstance.

1. INTRODUCTION

Today, agriculture is threatened by population growth, declining arable land per capita and water scarcity (Fedoroff et al., 2010; Satterthwaite, 2010). This problem is exacerbated and progress to make world without hunger going to be interrupted by climate change (Wheeler and Braun, 2013). Rice is the foremost staple food for more than 50% of the world's population, but recently farmers have experienced a downturn in productivity growth, which is partly associated with a land degradation, soil fertility loss, salinization, erratic rainfall, and extreme weather events (IFRI, 2009).

Sustainable agricultural innovations are needed to meet rising food demand in an environmentally and socially acceptable way. Also, over the next decades mankind will demand more food from fewer land and water resources. Essentially, we need to produce more food with fewer resources (Schneider *et al.,* 2011). To meet future needs for food, agriculture systems will need to evolve in ways that not only intensify production from available land (enhance land productivity), but also do this in a more water-efficient way (enhance water productivity) to ensure nutrition and food security while sustaining the associated ecosystems (Fedoroff *et al.,* 2010; Giovannucci *et al.,* 2012).

The goal of 'increasing or improving water productivity' implies improvement in the output or yield of a crop with the water that is currently in use or available (Passioura, 2006). It is now widely believed that achieving increases in agricultural water productivity is the key approach to mitigating water shortages and to reducing environmental problems.

Against the background of rising food demand, decreasing productivity growth, and environmental degradation, natural resource management technologies, such as the system of rice intensification (SRI), have been propagated, especially in a smallholder farm context (Stoop *et al.,* 2002; Uphoff, 2003; Noltze *et al.,* 2012). SRI principles focus on neglected potentials to raise yields by changing farmers' agronomic practices towards more efficient use of natural resources (Uphoff, 2007).

SRI method of rice cultivation was initially developed in Madagascar (Laulanié, 1993), but recently it has been widely promoted also in more than 50 countries by governmental and non-governmental organizations (http://sri.ciifad.cornell.edu/). This includes practices like the use of single seedlings of a young age, wide spacing, aerobic soil management, active aeration through mechanical weeding, and the use of organic sources of nutrients as much as available (Stoop *et al.,* 2002; Uphoff, 2008; Uphoff *et al.,* 2011). Many studies show widespread evidence for SRI's apparent yield gains of more than 50% (Ceesay *et al.,* 2007; Senthilkumar *et al.,* 2008; Africare *et al.,* 2010; Kassam *et al.,* 2011; Uphoff *et al.,*2011; Sinha and Talati, 2007; Uphoff, 2007; Thakur *et al.,* 2009, 2010a, 2010b; Zhao *et al.,* 2010; Kassam *et al.,* 2011) while reducing crop water requirements (Satyanarayana *et al.,* 2007; Chapagain and Yamaji, 2010; Zhao *et al.,* 2010; Thakur *et al.,* 2011; Ndiiri *et al.,* 2013).

Conventionally, water management for rice aims at keeping paddy fields continuously submerged. However, SRI practice incorporates water-saving techniques, i.e., keeping paddy soils moist but not continuously flooded, either by making minimum daily applications of water or by alternately wetting and drying (AWD). In rainfed areas, which amount to

54 million ha worldwide, rainfall is the only source of water to the field (Bouman *et al.,* 2007). In most of these areas, rice is grown only once in a year (in the rainy season), and most of the rainwater is lost from rice fields either by evaporation or by seepage and percolation that can cause groundwater contamination and environmental pollution. High costs of production, low productivity (both crop and water), and poor fertilizer use-efficiency are common features of rainfed rice.

A major problem in areas where rice is grown with rainwater is first to control excess water when there is heavy downpour, and to keep it from harming standing crops; and second, there is need to manage drought stresses when there is not sufficient rain. It is quite difficult to adopt any water-saving irrigation methods in rice cultivation in these areas during rainy season. A similar situation exists with the SRI method also, where farmers report that intermittent irrigation or AWD water management is very difficult to implement in some locations, and a reason for meager adoption and discontinuance of SRI 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 agronomic and soil manipulation (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 farmers to provide supplementary irrigation to their crop and results in increased income and food security (UNEP 2012). Similarly, a Multi-Purpose Farming (MPF) system developed with farmers in Cambodia that builds upon SRI productivity enables them to increase and sustain much greater productivity from their limited land resources by converting from their rice monoculture to diversified agriculture with pond culture as the pivotal innovation (CEDAC, 2007).

It is still unknown whether SRI methods can outperform conventional practices under rainfed conditions without supportive innovations in water management, whether the provision of drainage and supplementary irrigation can affect grain yield under SRI, and how land and water productivity in paddy areas can be maximized by combining SRI methods of rice cultivation as an agronomic strategy with diversification beyond rainfed rice production. Such a strategy, referred to here as Integrated SRI (ISRI), includes a pond/refuge within the rice paddy as an engineering solution. This study is the first effort to evaluate under controlled conditions the synergies that could be involved between various practices of farming systems that capitalize upon potential productivity gains from SRI methodology. As such it should have some interesting implications for household food security.

2. METHODOLOGY

This field experiment was conducted over two years at the Experimental Research Farm, Deras, Mendhasal in Khurda district, Odisha, India (20^0 30' N, 87^0 48' 10'' E) during the 2009/10 and 2010/11. The soil of the experimental site is classified as *Aeric Haplaquepts*, sandy clay-loam in texture (63% sand, 16% silt, and 21% clay) with pH of 5.5. Soil organic carbon content was low (1.11%). The mineral content 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}.

2.1. Experiment details

2.1.1. Experimental treatments

The experiment was laid out in randomized complete 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 two different water management regimes (Table 1). In addition, there was a fourth treatment which involved a rainwater harvesting structure with the purpose of enhancing rice-field productivity by including aquaculture and horticulture in the farming operation, in what is referred to here as 'Integrated SRI'.

- In the first treatment (C-RW), the rice crop was grown with conventional methods fully dependent on rainwater and without any supplemental irrigation, with the rationale of simulating farmers' real field conditions, serving as a control against which to assess possible improvements.
- In the other three treatments, a rice crop was grown with SRI methods adapted to rainfed conditions, introducing several variations in water management, and in the fourth treatment, some important changes in the farming system represented by the trials.
- In the second treatment (S-RW), water management was kept that same as in the C-RW treatment, meaning only rainwater was used. No supplemental irrigation was provided so as to understand whether practices of SRI management other than water management would have any impact on crop growth, its physiological performances and yield.

Table 1: Details of experimental treatments

Treatments for rice crop management	Symbols	Cropping system
Rice crop was grown with conventional method , and all rainwater was harvested and used in the field without any supplemental irrigation	C-RW	Rice only
Rice crop was grown with SRI methods and all rainwater was harvested and used in the field without any supplemental irrigation	S-RW	Rice only
Rice crop was grown with SRI methods, no stagnant water was kept in the field (excess rainwater was drained) and supplemental irrigation was provided as and when required	S-IW	Rice only
Rice crop was grown with SRI methods, no stagnant water was kept in the field (excess rainwater was stored in the refuge) and supplemental irrigation was provided from water conserved in the refuge as and when required	S-CW	Rice + Fish + Horticultural crops

- The third treatment (S-IW) had a drainage facility installed to keep the field moist but not saturated, draining excess rainwater from the field, and providing also supplemental irrigation from groundwater sources as and when irrigation was required to maintain soil moisture with the aim of maintaining SRI-recommended water management status (moist but unflooded soil).
- In a fourth treatment (S-CW), the farming system itself was diversified. Out of the plot area of 350 m2, rice was grown on an area of 270 m2, and a small pond was dug with a surface area of 35 m2 (10% of total plot area) and a depth of 2 m. The remaining 45 m2 of the 80 m2 area was for the refuge bunds (the design of this treatment is shown in Fig. 1). In this treatment, the rice crop was grown

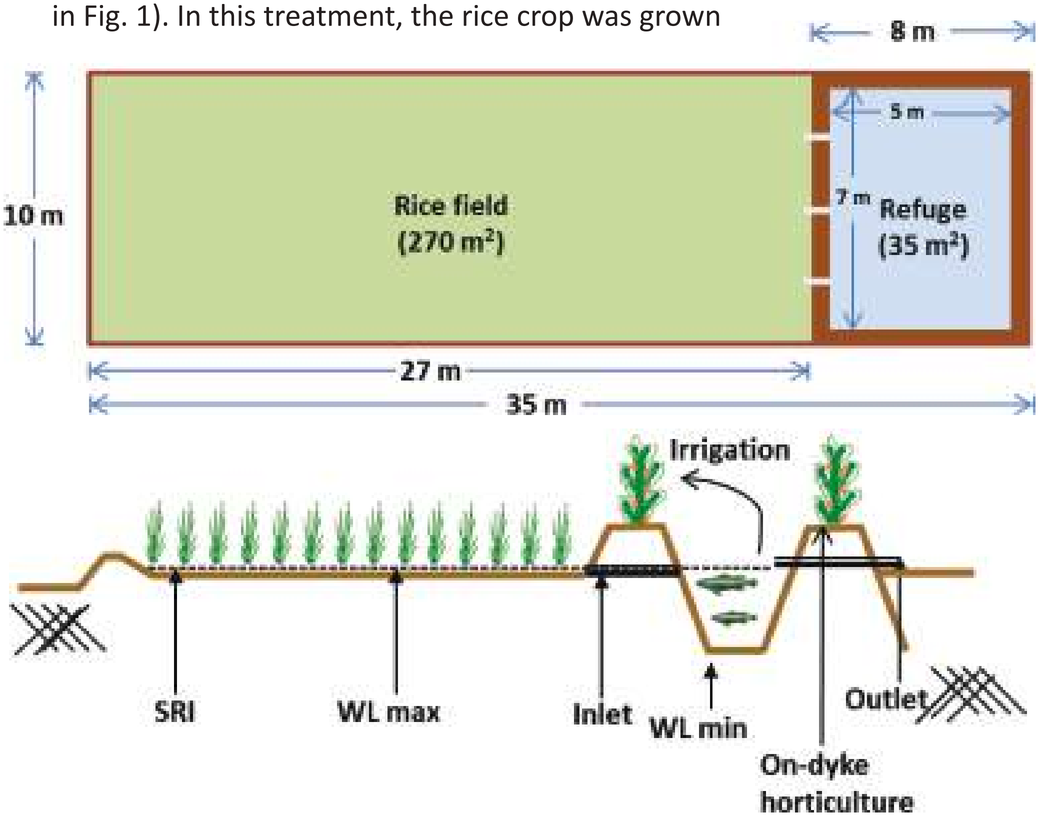

Fig.1 **Lay-out Design of Integrated System of Rice Intensification**

similar to S-IW, 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 for short-term periods, and the refuge bunds were used for 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 gives grain yields of 3.5 to 5.0 t ha^{-1} (DRD 2006), was planted on all four sets of treatments. Germinated seeds were sown in a nursery (18th July in 2009 and 15th July in 2010), and from there, 12-day-old single seedlings were transplanted for SRI plots at a spacing of 20 × 20 cm (25 plants m^{-2}) within 30 minutes after removal from the nursery; for the conventional method plots (C-RW), transplanting was done at 25-days, using three seedlings $hill^{-1}$ at a spacing of 20 × 10 cm (150 plant m^{-2}).

The SRI plots were weeded by cono-weeder *(http://www.ksnmconoweeder.com/)* at 10, 20 and 30 days after transplanting (DAT), while the conventional-method plots had three hand weedings at the same intervals. Fully decomposed cow dung manure (0.37% N, 0.19% P_2O_5 and 0.17% K_2O) was applied to the entire main field, i.e., to all the experimental plots, after completion of puddling, leveling and draining off of excess water. The manure was applied at the rate of 5 t ha^{-1}, along with chemical fertilizer applications of 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}), so all trial plots had the same nutrient amendments. All of the P was applied at the time of final land preparation, while N and K 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 with SRI is for organic soil and crop fertilization in preference to chemical fertilization; however, in this evaluation we did not make differences in fertilization an additional factor to be assessed. Soil nutrient amendments were thus not a variable in either amount or form in this experiment. Rice was harvested from each plot on 30th November, 2009 in the first year and on 28th November, 2010 in the second year of the experiment. However, it was noticed that SRI plots matured nearly 7 days earlier than conventional transplanted rice plots due to lesser transplanting shock period for the younger seedlings used in SRI.

2.1.3. Water management

Contrary to conventional rice cultivation of flooded rice, SRI methods recommend keeping paddy soil just moist with no stagnant water during the vegetative stage of crop growth (Stoop *et al.,* 2002). Average rainfall during the entire rice crop period (July-November) was 903 ha-mm. The C-RW and S-RW plots were cultivated entirely with rainwater except that in the S-RW plots, the rice crop was grown following SRI methods. S-IW plots were kept unflooded during the entire vegetative stage, and were then maintained with 2-3 cm ponding depth after panicle initiation. Excess rainwater was drained from these plots when it accumulated, and supplementary irrigations were provided when there was no rainfall for a longer period. A total of 350 and 213 ha-mm water was applied from external sources in the S-IW plots during 2009 and 2010, respectively. A similar amount of water was also applied in S-CW plots, but the source for this was conserved refuge water. Water was drained from all the plots at 15 days before rice harvest.

2.1.4. Fish and horticultural crops management

In treatment S-CW, short-duration fish culture of Indian major carps (IMCs) was undertaken, using harvested excess rainwater 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 an application of lime ($CaCO_3$) at the rate of 750 kg ha^{-1}, raw cattle dung (RCD) at 7000 kg ha^{-1} as a basal dose, and fertilizer (urea : single super phosphate :: 1:1) at 3 ppm.

Seven days after the refuge preparation, fish fingerlings of IMCs *(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 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 feed ingredients was 8.8 and 37.3, respectively, for the rice bran and mustard oil cake. Periodic manuring with RCD 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. Harvesting of fish was undertaken at 150 days after stocking (23rd January, 2010 and 25th January, 2011). Dwarf varieties of papaya and banana (15 each) were planted during July, 2009 alternately at a spacing of 2 m between plants on refuge bunds in the S-CW treatment with 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 total water used during this period in two years (8 months total) was 9600 liter.

2.2. Parameters measured

2.2.1. Water quality

Periodic observations on water quality parameters of both irrigation and refuge water, such as dissolved oxygen (DO), temperature, pH, turbidity; total alkalinity, total suspended solids, CO_2 and salinity, were monitored using standard methods (Mohanty *et al.,* 2009), and 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. Root parameters and xylem exudation rate

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

For measurement of the xylem exudation rate at the early-ripening stage, five 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 each stem. After 24 hours, 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).

2.2.2. Tiller and leaf number

Five hills were randomly selected from each replicate at the flowering stage for measurement of 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)

Leaf area was measured during the flowering stage using a leaf area meter (LICOR-3100 Area Meter), and a leaf area index (LAI) value was calculated by dividing the leaf area by the land area.

Light intensity above the canopy (I_0) and at the surface of the soil under the canopy (I_b) was measured with a Line quantum sensor (400-700 nm) (Model: EMS 7; SW & WS Burrage, UK) on a bright sunny day between 11:30 a.m. to 12:00 noon during the flowering stage. The light intensity at the surface of the soil relative to the intensity above the canopy was measured at consecutive points at intervals of 1 m apart in the inter-row space and in the inter-hill space, respectively (San-oh *et al.,* 2004). Light interception by the canopy (LIC) was calculated, as a percentage, from the following equation:

$$LIC = \left(1 - \frac{I_b}{I_0}\right) \times 100$$

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

At the flowering stage from each plot under all four treatments, five flag leaves and fourth leaves (4th from the top) were marked to measure chlorophyll fluorescence (Fv/Fm and ΦPS II) with a Fluorescence Monitoring System (FMS-2, Hansatech). Prior to each set of Fv/Fm measurements, leaves were dark-adapted for a period of 30 min using leaf clips.

The same leaves were also used to measure the photosynthesis rate with the use of a CIRAS-2 Portable Photosynthesis System (PP Systems, U.K.). These measurements were taken on a clear sunny day (solar radiation >1200 µmol m^{-2} s^{-1}) between 10:30 to 11:00 a.m. before the mid-day reduction in photosynthesis. After a measurement of photosynthesis, leaves were used to determine chlorophyll content through the dimethyl sulfoxide (DMSO) method (Hiscox and Israelstam, 1979), expressed in terms of mg g^{-1} fresh leaf weight.

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

Dry weight of plant samples was determined at harvest after oven-drying at 80°C for 72 h to reach a constant weight. All plants in an area of 5 × 5 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.

Harvest Index (HI) was calculated by dividing dry grain yield by the total dry weight of aboveground parts. Average panicle number was determined from the crop harvested from a square meter area from each plot. Panicle length, number of grains per panicle, and number of filled grains were measured for each panicle individually harvested from a square meter area from each plot. The percent of ripened grains was calculated by dividing the number of filled grains by the number of total grains.

1.2.6. Economic evaluation and water productivity

The ratio of the value of outputs to the cost of their cultivation in all four of the treatments was estimated. The cost of the excavated refuge, assuming a life span of 15 years, which is a fixed cost, was added (depreciated cost) to the yearly variable cost of cultivation. The cost of the excavated refuge was Rs. 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 time of irrigation were multiplied to know the quantity of irrigation water applied. Economic indices of water productivity (net water productivity [NWP], in Rs. m^{-3}) were estimated as a ratio of net profit from the cultivation system and total water used (irrigation + rain) (Mohanty *et al.,* 2009).

2.3. Data analysis

All data were analyzed statistically by analysis of variance (ANOVA) technique (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 with SAS 9.2 (SAS Institute Inc. Cary, NC, USA). The data set for all the parameters was statistically analyzed considering year as a source of variation in addition to the treatment. The effect of year and the interaction effects of year × treatments were not significant at $P < 0.05$ for most of the parameters, so the data reported in this paper are averages for the two years of trials.

3. RESULTS

3.1. Water quality in relation to crop production

The quality of water conserved in the refuge was compared with the irrigation water quality used for irrigation in S-IW plots. Conserved water had significantly higher amounts of DO, dissolved organic matter, total suspended solids (TSS), plankton, chlorophyll content, and nitrogen content compared to the irrigation water. It was seen that conserved water had significantly lower levels of alkalinity, phosphate, fluoride and chloride than the irrigation water (Table 2).

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
Total alkalinity (mg L^{-1})	74 ± 10	108 ± 8
Dissolved organic matter (mg L^{-1})	3.4 ± 0.4	1.6 ± 0.2
Total suspended solids (mg L^{-1})	265 ± 13	127 ± 17
NH4+ 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 x 10^3 ± 1.1	7 x 10^2 ± 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. Yield and yield contributing-characteristics

The highest rice grain yield was recorded in the S-CW treatments, followed by S-IW and S-RW (Table 3). The lowest rice yield was found in the treatments with conventionally-grown flooded rice, fully dependent on rainwater. The percentage increase in grain yield in the S-RW, S-IW and S-CW treatments over conventional method was, respectively, 53, 97 and 113%. It was evident from the results that enhancement in grain yield under SRI method was mainly due to improvement in the harvest index. It was further noted that 53% yield enhancement in S-RW compared to C-RW was due to differences in the method of rice cultivation, which resulted into significantly longer panicles with more number of grains and grain weight (Table 4).

On the other hand, improvement in grain yield in S-IW compared to S-RW was found to be 29%, mainly due to the unflooded field condition and the supplementary irrigation provided. Because of proper water management in S-IW treatment, there was significant improvement in panicle m^{-2}, panicle length, grains panicle^{-1}, and grain-filling. The yield improvement of 8% from S-CW compared to S-IW was due to irrigating the S-CW plots with stored refuge water which resulted in more number of panicles compared to the plots irrigated from groundwater sources in the S-IW plots.

Table 3: **Effect of rice production systems on grain yield, straw yield and harvest index (HI)**

Rice production system	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Harvest Index
C-RW	2.89 d	5.00 c	0.36 c
S-RW	4.41 c	6.38 b	0.41 b
S-IW	5.70 b	6.59 ab	0.46 a
S-CW	6.16 a	6.81 a	0.47 a

The different letters denote significant ($P < 0.05$) difference between treatments by DMRT

Table 4: **Effects of rice production systems on yield-contributing characteristics**

Rice production system	Ave. panicle number hill^{-1}	Panicles (m^{-2})	Ave. panicle length (cm)	Spikelet number/ panicle	Filled spikelets (%)	1000-grain weight (g)
C-RW	6.4 c	321.7 b	14.6 d	99.8 d	75.5 b	22.9 b
S-RW	13.2 b	328.8 b	18.2 c	119.5 c	74.9 b	24.3 a
S-IW	16.8 a	420.2 a	20.9 b	130.5 b	86.4 a	24.4 a
S-CW	17.2 a	428.8 a	22.0 a	146.9 a	86.5 a	24.4 a

The different letters denote significant ($P < 0.05$) difference between treatments by DMRT

3.3. Effects on root growth and activity

At the early-ripening stage, roots’ growth and their functionality were significantly affected by crop and water management practices. Rice plants grown with SRI practices had two to three times more root dry weight and amount of exudates transported from roots towards shoots per hill compared to rice crops that were grown following conventional rainfed management (Table 5). In spite of the much lower plant populations under SRI, a similar trend was also found on a unit-area basis. The data clearly indicated better root growth and performance under SRI methodology during the early-ripening stage of the crop. Among different SRI management systems, the highest root dry weight and amount of xylem exudates was found in the rice grown with no standing water on the field and with the irrigation provided from conserved refuge water (S-CW).

Table 5: 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)	
	Per hill	Per m^2	Per hill	Per m^2
C-RW	4.1 d	206.3 c	2.26 d	113.2 d
S-RW	7.5 c	187.0 d	5.38 c	134.6 c
S-IW	10.2 b	254.3 b	7.19 b	179.8 b
S-CW	12.3 a	308.0 a	7.82 a	195.4 a

The different letters denote significant *($P < 0.05$)* difference between treatments by DMRT

3.4. Effects on plant morphology (plant height, tillering, and leaf number), LAI and LIC

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 6). The tallest plant was grown under the S-CW treatments, about 22% taller than C-RW. SRI practice also significantly increased the number of tillers per hill compared with conventional flooded rice.

Crops grown under SRI with unflooded conditions and supplementary irrigation (S-IW and S-CW) had significantly higher numbers of tillers per hill than SRI fields grown under uncontrolled rainwater (S-RW). However, the number of tillers per unit area was lowest under S-RW, and no significant differences were found between other treatments.

In spite of significantly lower number of tillers per hill under C-RW, the tiller numbers in unit-area terms were comparable with other treatments mainly due to the greater number of hills per unit area under C-RW. 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-RW, but there were no significant differences in number of leaves in unit-area terms among C-RW, S-IW and S-CW. The lowest number of leaves m^{-2} was found in S-RW plots.

Leaves' interception of incidental solar radiation and the leaf area index (LAI) are widely used parameters for growth analysis (Yoshida, 1981). Leaf area index was significantly higher in plots with SRI method of cultivation than for rice grown under conventional flooded method (Table 6). Highest LAI was found under the S-CW treatment, followed by S-IW and S-RW.

In spite of comparable leaf number among C-RW, S-IW and S-CW, 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-RW crop. In the S-CW treatment, the highest light interception by the canopy was observed.

Table 6: **Effects of rice production system on morphological characteristics, leaf area index (LAI) and light interception by canopy (LIC) at flowering stage of development**

Rice production system	Plant height (cm)	Ave. tiller number (hill^{-1})	Tiller number (m^{-2})	Leaf number (hill^{-1})	Leaf number (m^{-2})	LAI	LIC (%)
C-RW	99.1 d	9.8 c	490.8 a	40.7 d	2033.3 a	2.74 d	75.1 c
S-RW	110.1 c	16.2 b	404.6 b	71.0 c	1775.0 b	3.26 c	80.6 b
S-IW	116.7 b	18.4 a	460.8 a	81.3 b	2033.3 a	3.86 b	83.1 b
S-CW	121.3 a	19.2 a	480.0 a	87.0 a	2175.0 a	4.13 a	87.6 a

The different letters denote significant ($P < 0.05$) difference between treatments by DMRT

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

The leaf chlorophyll content, maximum quantum efficiency (Fv/Fm), actual quantum efficiency (Φ PS II), and photosynthetic rate were all significantly greater in plants grown under SRI practice compared to conventional method at flowering stage (Table 8). Among different SRI treatments, these parameters were found highest among plants grown under S-CW than others. This indicates that the plants grown with S-CW method had significantly greater maximum and actual quantum efficiency, an indicator of light utilization capabilities of the leaves for light reaction of photosynthesis and CO_2 fixation than did the plants grown under other cultivation methods. Leaves of rice crop grown under S-CW had photosynthesis rates nearly double those of leaves for the C-RW crop. This might be due to greater leaf chlorophyll content that was evident from the data shown in Table 7.

Table 7: Effects of rice production system on leaf chlorophyll content, chlorophyll fluorescence quantum yield (Fv/Fm and ΦPS II), and photosynthesis rate at flowering stage of development

Rice production system	Chlorophyll content (mg g^{-1}leaf FW)	Fv/Fm	ΦPS II	Photosynthetic rate (µmol m^{-2} s^{-1})
C-RW	2.26 d	0.697 c	0.418 d	12.96 d
S-RW	2.61 c	0.726 b	0.522 c	15.49 c
S-IW	3.01 b	0.789 a	0.585 b	21.54 b
S-CW	3.39 a	0.806 a	0.631 a	24.01 a

The different letters denote significant *($P < 0.05$)* difference between treatments by DMRT

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

After 150 days of rearing, a fish harvest was made from the S-CW plots in January of both years. 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, with an average yield of 2.6 t ha^{-1}. Also from the S-CW plots, a total of 1,050 kg of papaya and 30 bunches of banana were harvested from the bund areas of 45 m^2 of each refuge (from 15 trees each) in the two years with an average 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 averaged Rs.10,050 from the bund area of each S-CW refuge.

Net profit from this Integrated SRI system (including rice, fish and horticultural crops) was significantly higher than from the other three systems. 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. 4,371 ha^{-1} in the two years). Concurrently, the Integrated SRI system with a similar area and same duration of two years produced a net profit of Rs. 9,401 (equivalent to Rs. 268,600 ha^{-1} in the two years). The OV: CC ratio indicated that in the Integrated SRI system, for an investment of Rs.1 a farmer can get a return of Rs. 2.97, almost three times back. The conventional upland paddy cultivation, on the other hand, was not much more than a break-even operation (OV: CC ratio: 1.13). The net water productivity (NWP) in the Integrated SRI system was Rs 18.91/ m^3 of water (S-CW), while it was only Rs. 0.31/ m^3 of water in conventional rice cultivation system. This indicates a significant economic gain per volume of water under integrated SRI system (Table 8).

Table 8: **Economic analysis of different rice production systems (combined values from 2 years experiment)**

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

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

[b] In S-CW system, out of 350 m^2 area- 270 m^2 was used for rice cultivation, 35 m^2 was refuge area used for fish culture and rest 45 m^2 area was under bund 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 and Rs. 125/ bunch, respectively.

INR 55.5 = 1 USD

4. DISCUSSION

Too much water use in rice cultivation not only lowers water productivity; it also leads to excessive NO_3–N leaching, which causes environmental pollution with degradation of ground and surface water quality. The challenge of enhancing water productivity 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 (Bouman, 2007; Ali and Talukder, 2008; Nangia *et al.,* 2008; Sandhu *et al.,* 2012), most importantly is using water-saving irrigation methods in rice field. Water-saving irrigation 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. Most of the time these methods enhance water productivity, but with the cost of lower grain production (Bouman and Tuong, 2001; Tuong and Bouman, 2003; Tuong *et al.,* 2005).

In recent years, the System of Rice Intensification (SRI) has generated considerable interest among farmers, researchers, NGOs, print media, and governments. SRI includes transplanting young, single seedlings at wide spacing, compost application as much as available, soil-aerating mechanical weed control, and keeping fields moist or alternate wetting and drying during the vegetative growth stage of the crop cycle (Stoop *et al.,* 2002). Most evaluations on SRI report yield advantages over conventional management of irrigated rice (Kassam *et al.,* 2011). There are also some reports of no yield increases with SRI management over conventional practice, however (Sheehy *et al.,* 2005; Latif *et al.,* 2005, 2009; McDonald *et al.,* 2008). A few other researchers have found no yield gain with SRI method compared to conventional method of rice cultivation, but have documented some significant improvement in water productivity (Krupnik *et al.,* 2012a; Krupnik *et al.,* 2012b; Singh, 2013; Singh *et al.,* 2013; Suryavanshi *et al.,* 2013) due to reduced water use in the SRI method.

Adopting any water-saving methodology of rice production or irrigation method recommended for SRI methods (keeping fields unflooded) during the wet or rainy season is quite difficult in the field as a substantial amount of rainfall occurs over a few months, and at times there can be either heavy rainfall or long dry spells occurring in most of the Asian countries. Under these situations, a rice crop faces the problems of having too much water, which inundate paddies and suffocate roots, and/or prolonged or intense dry spells that stress the rice plants. Either or both ultimately result into poor crop productivity. These stresses become more hazardous if the rice plants affected have not developed deep and healthy root systems.


Integrated SRI field with refuge

As SRI was developed for irrigated rice production, most of the evaluations have been done for such conditions. Here we were interested first in (a) whether SRI practices excluding suggested AWD irrigation had any significant effect, positive or negative, on grain yield and production under rainfed conditions, and second in (b) whether SRI practices

perform better, if we keep paddy field unflooded with a provision of irrigation / drainage facilities. Finally, (c) we wanted to explore how best rainwater can be conserved and utilized in rice fields for further enhancing land and water productivity, and further, with what if any positive effect on net income by using SRI methods for rice cultivation while utilizing stored water for aquaculture and horticulture.
In the S-RW treatment, the SRI method included practices like: transplanting of single, younger seedling at wider spacing and using a soil-aerating mechanical weeder, being fully dependent on rainwater without any recommended AWD irrigation. These practices were able to enhance rice production by 53% compared to conventional practice of rainfed rice cultivation, transplanting three older seedlings hill^{-1}, closely spaced and with hand weeding (Table 3).

The research indicated that adoption of some of the practices of SRI method, even under rainfed conditions, provided a better growing environment and produced rice plant hills that had significantly more roots, tillers and leaves. At the flowering stage, SRI plants showed significant improvement in their morphology, with significant increases in plant height, tillering and increased leaf size, and higher leaf area index responsible for greater light interception. Therefore, these practices improve root growth and functioning while also making for a larger, healthier canopy. Any improvements in the above-ground shoots and canopy concurrently benefit the roots, and vice versa (root-shoot interaction).

In our previous work on irrigated SRI management, we reported that improvements in the basic morphological characteristics of rice plants grown under irrigated SRI lead to better physiological functions, maintaining a higher rate of photosynthesis during flowering and ripening stages, producing more filled grains and heavier grains, and thereby improving grain yield (Thakur *et al.,* 2011). Some of the individual practices of SRI method that were followed here have been shown to be responsible for yield increases under irrigated rice cultivation, e.g., use of single seedlings (San-oh *et al.,* 2006), younger seedlings (Pasuquin *et al.,* 2008), and wider spacing (Thakur *et al.,* 2010a). However, while growing rice with SRI methods during the rainy season, there should not be any stagnant water on the field during the initial 7-10 days after transplanting, because smaller seedings are transplanted; otherwise there is a possibility that small seedlings may die in standing water on the field.

It is interesting to note that in the S-IW treatment, further improvement in grain yield was found when excess rainwater (no stagnant water) was drained from the field and supplemental irrigation was provided. Keeping the field unflooded and applying water to minimize any water stress significantly improved root growth and activity; in turn, crop growth, canopy development and physiological performances resulted into enhanced grain yield.

Earlier, Zhang *et al.,* (2009) similarly concluded that keeping the paddy field unflooded and following a regime of moderate wetting and drying irrigation significantly increases 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 sucrose to-starch conversion in grains. These changes result in higher grain yield compared to continuously-flooded rice field results. Also, crops under SRI method with their greater and more active roots help to increase N-uptake and maintain higher N-content in their leaves than with conventionally-grown flooded- rice (Zhao *et al.,* 2009; Thakur *et al.,* 2013).

Since ancient times in villages of India, Sri Lanka and other Asian countries, rainwater has been harvested by directing surface runoff into reservoirs or on-farm ponds or cisterns for supplementary irrigation (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 have been constructed to capture drainage water coming out of rice fields (Mushtaq *et al.,* 2006). Oweis and Hachum (2006) have demonstrated that water harvesting and supplemental irrigation improved 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.

With integrated SRI methods (S-CW), excess water was saved in a small refuge and used for need-based supplementary irrigation for the rice crop and also used for maintaining aquaculture and for irrigating horticultural crops. Due to harvesting water from the rice field runoff and providing feed to the pond to support aquaculture, the pond water became nutrient-rich as evident from water-quality parameters presented in Table 2. Using this nutrient-rich pond water for irrigating

Demonstration field of ISRI

rice, grain yield increased by 8% compared with rice irrigated with groundwater sources. Additional income was generated from fish culture in the small pond and horticultural crops grown on the bund of pond. In this way, net water productivity was multiplied more than 60-fold, from Rs. 0.31/ m^3 in conventional rainfed rice system to Rs 18.91/ m^3 in Integrated SRI system.

This study demonstrated that use of SRI practices improved water productivity by producing more grain output, which was further improved by provision of drainage and applying supplementary irrigation, and integrating SRI method of rice cultivation with aquaculture and horticulture. This method enhances food security and livelihoods for the smallholder by managing water for both rice and fish along with horticultural crops on a compact land area.

5. CONCLUSIONS

The results of the present field investigation revealed that SRI practices improve the grain yield due to improvements in several key morphological characteristics of the rice crop and in the plants' physiological performance over the conventional transplanting methods. SRI management enhanced the productivity of water by producing more grain, which can be further improved by providing supplementary irrigation.

Harvesting and storing excess rainwater within the rice field in a pond or refuge provides options for integrating aquaculture with rice cultivation and for growing horticultural crops on the refuge bunds, significantly improving water productivity under rainfed conditions, which are normally prone to crop failure, lower productivity, and making the environment polluted under conventional management. SRI alternatives look promising for helping to solve problems of food security under erratic changes in precipitation pattern and climate-change future conditions.

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