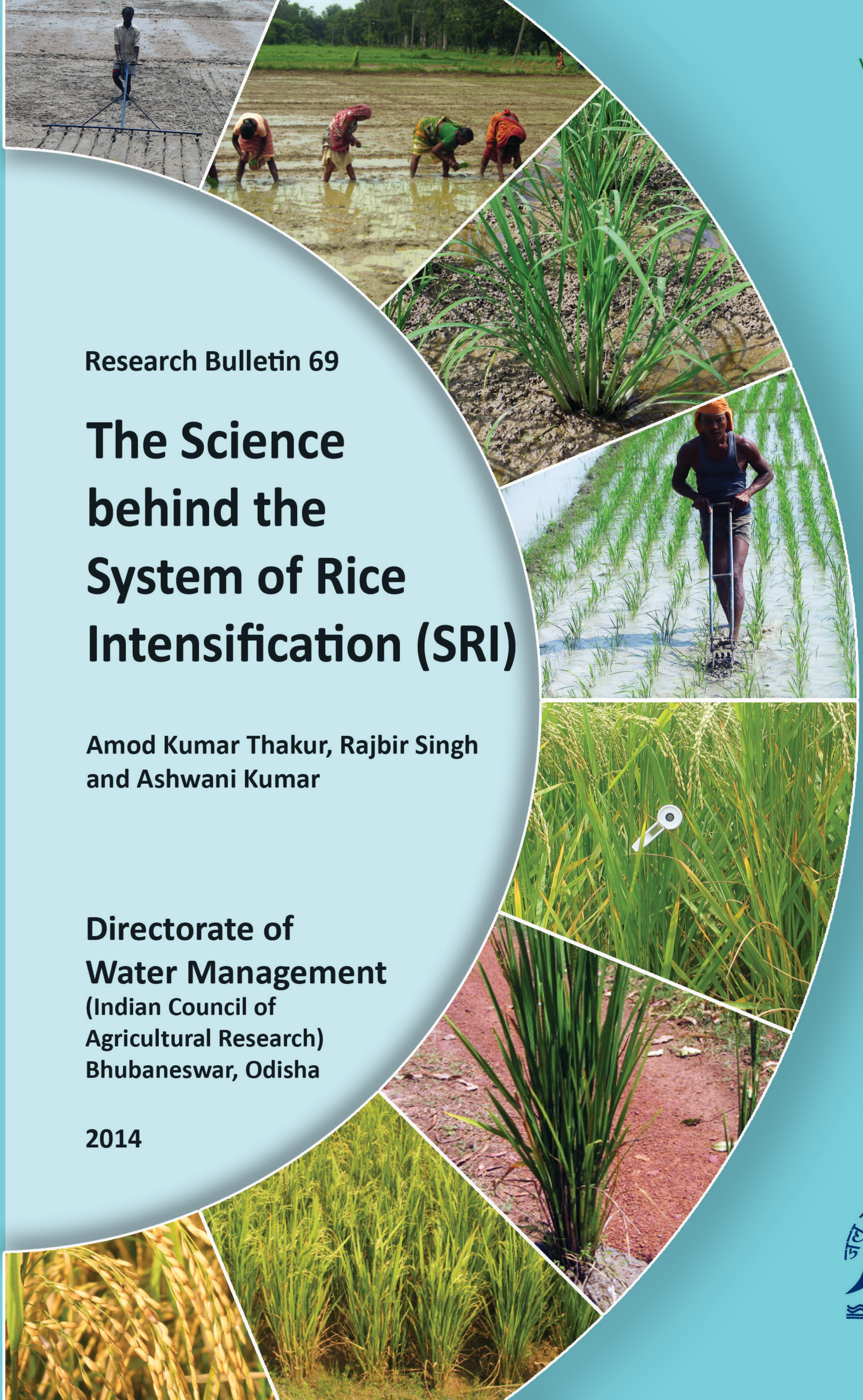

Research Bulletin 69

The Science behind the System of Rice Intensification (SRI)

Amod Kumar Thakur, Rajbir Singh
and Ashwani Kumar

Directorate of
Water Management
(Indian Council of
Agricultural Research)
Bhubaneswar, Odisha

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भाकृअनुप
ICAR

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Correct citation

Thakur, A.K., Singh, Rajbir and Kumar, Ashwani 2014. The Science behind the System of Rice Intensification (SRI). Research Bulletin No. 69, Directorate of Water Management (ICAR), Bhubaneswar, Odisha, India, 58 p.

Published by

Director
Directorate of Water Management
(Indian Council of Agricultural Research)
Bhubaneswar-751023, Odisha, India
August, 2014

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Printed at

S J Technotrade (P) Ltd.
Subarnarekha Chambers,
Plot No : A-9 & 10, Unit – IV,
Bhouma Nagar, Bhubaneswar – 751001
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Preface

World agriculture is facing one of the largest challenges in the 21st century: how to produce enough food to feed 9 billion people by 2050, with limited land, water and nutrient resources, and reduce negative environmental harm simultaneously for sustainable development.

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 meet the consumption needs of the growing population, global average rice yield needs to be increased by 12% over the yield level of 2005 by 2015. Asia harvests about 90% of the world's rice, however, Asia has not seen any rice yield increase in the past decade. Greatest challenge for rice farming is water scarcity. Irrigated rice accounts for about 80% of the total freshwater resources used for irrigation in Asia, but the current water use efficiency for rice is about two times smaller than wheat. Irrigated rice production requires large amounts of water, with 1 kg of rice grain requiring 2500 liter of water. 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.

The question arises - for researchers, for policy makers, and especially for farmers - what should be done now for an encore? Can we succeed in meeting the food needs for our still-growing populations by doing essentially more of the same? Or must some other directions be developed?

The System of Rice Intensification (SRI), developed by French Fr. Henri de Laulanié, S.J., involves cultivating rice with as much organic manure as possible, starting with young seedlings planted singly at wider spacing in a square pattern; and with intermittent irrigation that keeps the soil moist but not inundated, and frequent inter-cultivation with weeder that actively aerates the soil. SRI method of rice cultivation is now being practiced in more than 50 countries. This spread in a decade's time is due to the fact that it addresses many of the challenges faced by rice farmers across the world.

A team of scientists from Directorate of Water Management (ICAR), Bhubaneswar, conducted research to find out physiological basis of yield enhancement under SRI method of rice cultivation and tried to understand 'The science behind the SRI practices'. 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 'grow more rice with less water'.

- Authors

Executive Summary

Rice is life for more than half of humanity. It is the grain that has shaped the cultures, diets, and economies of billions of people in the world. Food security in the world is challenged by increasing food demand and threatened by declining water availability. Exploring ways to produce more rice with less water is essential for food security. The System of Rice Intensification (SRI), a new method of rice cultivation, offers an opportunity for reducing water demand accompanied by yield enhancement of rice. SRI management involves many departures from the methods conventionally recommended for rice cultivation. It proposes the use of single young seedlings, drastically reduced plant densities, keeping fields unflooded, use of a mechanical weeder which also aerates the soil, and enhanced soil organic matter. These practices have the aim of providing optimal growth conditions for the plant, to get better performance in terms of yield and resource productivity.

Field experiments were conducted to investigate whether practices of the System of Rice Intensification (SRI), could improve rice plants' morphology and physiology and what would be their impact on resulting crop performance, compared with currently recommended scientific management practices (SMP). With SRI practices, grain yield was increased by 48% in these trials at the same time, there was average water saving of 22% compared with inundated SMP rice. Water productivity with SRI management practices was almost doubled (0.68 g l^{-1}) compared to SMP (0.36 g l^{-1}). Significant improvements were observed in the morphology of SRI plants in terms of root growth, plant/culm height, tiller number per hill, tiller perimeter, leaf size and number, leaf area index (LAI), specific leaf weight (SLW), and open canopy structure. These phenotypic improvements of the SRI crop were accompanied by physiological changes: greater xylem exudation rate, crop growth rate, mean leaf elongation rate (LER), and higher light interception by the canopy compared to rice plants grown under SMP. SRI plants showed delayed leaf senescence and greater light utilization, and they maintained higher photosynthetic rates during reproductive and grain-filling stages. This was responsible for improvement in yield-contributing characteristics and higher grain yield than from flooded rice with SMP. We conclude that SRI practices improve rice plants' morphology, and this benefits physiological processes that result in higher grain yield and water productivity.

1. INTRODUCTION

Due to ‘Green Revolution’, world rice production nearly doubled from the 1960s to the 1980s. The Green Revolution comprised the replacement of traditional cultivars with modern cultivars responsive to increased external inputs like chemical fertilizer, irrigation water and pesticides. The expansion of this technological package was also supported by the political incentives to construct irrigation infrastructure and to subsidize chemical inputs. After the wide spread of the ‘‘Green Revolution” throughout irrigated paddy fields in Asia, however, the rice yield increase has slackened, reflected by the decline in the annual rate of rice yield increase from 2.7% in the 1980s to 1.1% in the 1990s. The existing system of paddy production, particularly green revolution input intensive technology favours cash rich farmers. Increasing prices of agricultural inputs prevent poor farmers from completely adopting modern production technologies. Excessive use of agrochemicals (chemical fertilizers and pesticides/ insecticides) also damages soil biota and creating environmental pollution.

Today agriculture faces two major challenges. First, it needs to enhance food production sustainably to feed a growing world population; at the same time, this increase needs to be accomplished under conditions of increasing scarcity of water resources (Bouman, 2007) and scarce availability of new land for agriculture. Rice (*Oryza sativa* L.) is the foremost staple food for more than 50% of the world’s population. It is estimated that by the year 2025, the world’s farmers should be producing about 60% more rice than at present to meet the food demands of the expected world population at that time (Fageria, 2007). Irrigated rice production is the largest consumer of water in the agricultural sector, and its sustainability is threatened by increasing water shortages. Such water scarcity necessitates the development of alternative irrigated rice systems that require less water than traditional flooded rice (Bouman et al., 2005).

To improve resource use efficiency, it will be necessary to address the growing concerns regarding water scarcity, higher fertilizer costs, and negative environmental impacts due to the increasing use of agrochemicals for rice production. Some possible solutions include breeding superior genotypes under water-saving rice-cultivation methods (aerobic rice; Atlin et al., 2006), improving water management (Shi et al., 2002; Yang et al., 2004) and fertilizer use efficiency via more frequent split applications (Dobermann et al., 2000). In such a situation, the System of Rice intensification (SRI), which is a low-cost and high yielding system, might be a sustainable alternative to conventional paddy production (Tsujimoto et al., 2009).

The System of Rice Intensification (SRI) developed in Madagascar over 30 years ago (Laulanié, 1993) is reported to offer an opportunity for reducing water demand accompanied by yield enhancement of rice (Chapagain and Yamaji, 2010; Satyanarayana et al., 2007; Thakur et al., 2010, 2011; Uphoff, 2007; Zhao et al., 2010).

SRI management involves many departures from the methods conventionally recommended for rice cultivation. SRI proposes the use of single young seedlings, drastically reduced plant densities, keeping fields unflooded, use of a mechanical weeder which also aerates the soil, and enhanced soil organic matter. These practices have the aim of providing optimal growth conditions for the plant, to get better performance in terms of yield and resource productivity (Stoop et al., 2002).

Although most published and unpublished reports on SRI tend to be optimistic, they are incomplete in their coverage of the existing scientific literature, and there is a general lack of detailed field research following high scientific standards. So far mostly on-farm trials were conducted on SRI at different Asian countries; there is still need to improve the understanding and spread of this innovation and to undertake critical experiments on SRI. Little is known about how SRI practices, affect rice plants' morphology, their physiology, and the implications of any changes for crop performance in terms of grain yield and water saving. This study investigated whether SRI practices, could have significant effects on plant growth, development, and subsequently on grain yield and water productivity.

A detailed comparison is presented in this report on the performance of rice plants grown with SRI management practices and plants that were raised according to currently-recommended scientific management practices (SMP) which include the flooding of fields. Soil and climatic conditions, fertilization, and rice variety (genotype) were the same for both sets of trials.

1.1 Rice Cultivation in India

India has the world's largest area devoted to rice cultivation, and it is the second largest producer of rice after China. India provides around 21% of global rice production from its 28% of the world's rice area. Over half of its rice area is irrigated, contributing 75% of the total production. Notably, this area also consumes 50-60% of the nation's finite freshwater resources. Of the country's 1.15 billion inhabitants, 70% rely on rice for at least a third of their energy requirements. India's population is projected to grow to 1.6 billion in 2050, putting tremendous future strain on its land and water resources (Thiyagarajan and Gujja, 2012).

In India, rice is grown mostly in two major seasons, kharif (June -October) and rabi (October - February), while in some parts it is grown throughout the year in more than two seasons. Most of the rice area and production are in the kharif season, but rice productivity in terms of yield is 57% higher in the rabi season. Grain production in the mid-1960s, before the Green Revolution began, was about 60 million tonnes per annum. Thirty years later, production had grown to twice that, around 120 million tonnes, but the pace of growth has slowed since the late 1990s. The highest annual average increase in grain production was 6.1%, recorded during the 1980s; but the annual increase in grain production dropped to 1.5% in the 1990s.

During 2009, the state of West Bengal had the largest rice area in the county and also the highest paddy production. Rough rice productivity was below 3 t ha^{-1} in Assam, Bihar, Gujarat, Himachal Pradesh, Jammu & Kashmir, Jharkhand, Maharashtra, Odisha, and Rajasthan; and below 2 t ha^{-1} in the states of Chhattisgarh and Madhya Pradesh. In fact, the country's average productivity (3.31 t ha^{-1}) is lower than all the neighbouring countries of Southeast Asia. The Asian average is 4.23 t ha^{-1}, while the world is averaging 4.18 t ha^{-1}.

During the period 1960-1961 to 2007-2008, the productivity increase in India has been lower (122%) than the global increase (131%). In this period, China achieved an increase of 248% from 1.9 t ha^{-1} to 6.61 t ha^{-1}. Globally, Australia with 13.5 t ha^{-1} in 2007-2008 ranked number one in rough rice productivity, followed by Egypt (10.1 t ha^{-1}).

1.2 Concerns in Rice Production

Much of the Green Revolution's gains have been achieved through highly intensive agriculture that depends heavily on high inputs like water and chemical fertilizers, resulted in damaging the soils, fresh water cycles and supplies, crop diversity and polluting environments. Rice production today faces a number of problems that threaten many rice-producing Asian countries' ability to meet the food needs of their rapidly growing populations. These constraints include pest outbreaks, diseases, soil degradation, water scarcity, conversion of rice lands for industrial use, soil salinization, and adverse soil conditions. Also, the gains due to modern expensive rice technology have bypassed most of the resource poor areas, which are pre-dominated by small and marginal farmers.

Enhancement in rice production is mainly attributed to productivity-led increases since the harvested rice area for the corresponding period expanded only by 42%, from 31 m ha to about 44 m ha. Grain demand in India is estimated to reach about 300 million tonnes per annum by 2020, necessitating an increase of about 91 million tonnes from the estimated 2005-2006 production level of 209 million tonnes. Since there is no probability of much further increase in the area under cultivation over the present 142 million ha, the needed 37% increase in grain production will have to be attained by enhancing the productivity per unit area. The production of milled rice per hectare has to be increased from 2,077 kg to 2,895 kg by 2020, an average annual increase of about 5%. This is three times more than the expansion rate during the 1990s. Rice cultivation is in crisis the world over, and India is no exception with its shrinking area of rice cultivation, its fluctuating annual production levels, stagnant yields, water scarcity, and escalating input costs. The cost of cultivation of paddy has consistently been increasing, owing to escalating costs of labour and agrochemical inputs. With increasing labour scarcity due to urbanization, sustaining the interest of the farmers in rice cultivation itself has become a challenge.

Current productivity in India is much lower than many other rice-producing countries, and it needs to be enhanced under the circumstances of little hope for increased in area and irrigation potential. During the last decade, the percent of irrigated rice area has been fluctuating around 53%, showing no appreciable increase.

Under present scenario concerns in rice production could be summarized as follows:

- Vagaries of monsoon are causing droughts and floods
- Increases in grain productivity have stagnated
- Factor productivity is declining continuously
- Management and efficiency of the country's surface irrigation systems are in serious disarray
- Groundwater resources are being over utilized, so water table is falling
- Soil quality is declining
- Subsidizing chemical fertilizer is proving to be very expensive
- Excessive focus on varietal changes for productivity enhancement
- Existing extension systems are overstretched
- Labour scarcity is threatening the continuance of rice farming

It is necessary that these challenges be met with care, consistency, and a positive approach to achieve national and household food security.

1.3 Water Crisis

Rice, as a submerged crop, is a maximum consumer of water and is the most widely grown of all crops under irrigation. To produce 1 kg of grain, farmers uses 3000-5000 liters of water. In Asia, more than 80% of the developed freshwater resources are used for irrigation purposes; about half of which is used for rice production (Dawe et al., 1998). Rapidly depleting water resources threaten the sustainability of the irrigated rice and hence the food security and livelihood of rice producers and consumers (Tuong et al., 2004). In Asia, 17 million hectare (Mha) of irrigated rice areas may experience ‘physical water scarcity’ and 22 Mha may have ‘economic water scarcity’ by 2025 (Tuong and Bouman, 2002). There is also much evidence that water scarcity already prevails in rice-growing areas, where rice farmers need technologies to cope with water shortage and ways must be sought to grow rice with lesser amount of available water (Tuong and Bouman, 2002).

India’s post-independence agricultural growth involved huge investments in irrigation projects that have resulted in more than a tripling of the gross irrigated area, going from 22.6 million hectares (1950-1951) to 76.3 million hectares (1999-2000). This has contributed to a drastic reduction in per capita fresh water availability, from 5,410 cubic meters to 1,900 cubic metres during that period. The greatest growth of irrigation has been through the installation of wells. In some regions, the over-exploitation of groundwater supplies through pump extraction is leading to serious declines in ground water levels. India is the largest user of groundwater in the world (over a quarter of the global total); 60% of irrigated agriculture and 85% of drinking water supplies in India are dependent on groundwater extractions.

According to the World Bank, if current trends continue, within 20 years, about 60% of all aquifers in India will be in a critical condition. This will have serious implications for the sustainability of agriculture, long-term food security, livelihoods, and economic growth. It is estimated that over a quarter of the country’s harvest will be at risk. There is thus an urgent need to change the status quo. The ‘Report of the Expert Consultation on Bridging the Rice Yield Gap in the Asia-Pacific Region’, published by the FAO in October 1999 says: “Countries like India and China are approaching the limits of water scarcity.” Experts have estimated that by 2025, the gap between the supply of, and demand for, water for irrigation in India will be 21 billion cubic meters (BCM). In addition to this absolute water constraint, other factors such as improper management of available water resources, sub-optimal farm management, poor crop husbandry, ineffective infrastructure, and unplanned capital development continue to subvert agriculture in India.

The future of country's rice production will depend heavily on developing and adopting strategies and practices that will use irrigation water more efficiently at farm level. To meet its food security needs, the country needs its increase its paddy production at the rate of 3.75 million tonnes per year until 2050. The paddy productivity in most states must be considerably enhanced from the current level.

1.4 Water Savings Technologies in Rice Cultivation

Several water-efficient rice production systems, such as using water-saving irrigation systems (alternate wetting and drying, AWD (Bouman and Tuong, 2001; Belder et al., 2004, 2007; Zhang et al., 2008), continuous soil saturation (Tuong et al., 2004), and sprinkler irrigation (Muirhead et al., 1989) and rice production systems using less-water (direct-dry seeding (Tabbal et al., 2002) aerobic rice culture (Nie et al., 2012; Kato et al., 2009) and system of rice intensification (Stoop et al., 2002)) have been found to be effective in reducing water use and improving water productivity, but often involve reduced grain yield, increased costs and more precise irrigation water control (Bouman et al., 2007). Farooq et al. (2009) discussed various strategies for producing more rice with less water.

Aerobic rice is grown like an upland crop such as wheat, under nonflooded conditions in non-puddled and unsaturated (aerobic) soil (Bouman and Tuong, 2001). With appropriate management, the system aims for yields of at least 4-6 t ha^{-1}. The usual establishment method is dry direct-seeding and can be rainfed or irrigated. Irrigation can be applied through flash-flooding, furrow irrigation (or raised beds), or sprinklers. Aerobic rice can save as much as 50% of irrigation water in comparison with lowland rice. Weed infestation is the most severe constraints to widespread adoption of aerobic rice (Rao et al., 2007). Weed pressure in dry direct-seeded aerobic rice is significantly greater than that recorded in transplanted rice (Singh et al., 2008). Weeds in plots with a lower seeding rate have more chances to emerge, grow, and build up a strong population and thus pose a serious crop-weed competition. Mahajan et al. (2010) recommended a higher seeding rate to reduce weed biomass in dry direct-seeded aerobic rice.

There are reports that alternate wetting and drying (AWD) may reduce, rather than increase, grain yield due to the loss of nitrogen, reduction in shoot biomass, and a shortened grain-filling period (Mishra et al., 1990; Tabbal et al., 2002; Belder et al., 2004). However, some recent reports have showed that compared with continuously submerged conditions, AWD can maintain or even increase grain yield because of the enhancement in root growth, grain-filling rate, and remobilization of carbon reserves from vegetative tissues to grains (Tuong et al., 2005; Yang et al., 2007; Zhang et al., 2008; Zhang et al., 2009a). These differences in results may be attributable to the effects of associated crop management practices rather than to water regime alone and also on degree of wetting and drying of field.

1.5 Need for Ecologically-sound Cultivation Techniques

Crisis in production, growing demand for rice and environmental degradation is the global challenge. There is an urgent need to find ways to grow more rice but with less water and less agrochemical inputs. The yield potential of rice, despite decades of investment in plant breeding, has remained relatively unchanged since the introduction of the first semi-dwarf variety (IR-8) in the mid-1960s. Agricultural experts and governments are prompted to look at other practical ways of increasing rice production without further degrading ecosystems.

Today, there are no known technical solutions presently available to improve rice productivity significantly with less water and without creating environmental pollution. Researchers at IRRI, Philippines aiming to 'supercharge' rice photosynthesis and trying to switch the rice carbon metabolism from a so-called 'C_3' pathway to a 'C_4' pathway by re-engineering, so that rice plants capture greater carbon and turn it into biomass (Barta, 2007; Normile, 2006). Researchers believe that discovering a way to convert rice from a C_3 into a C_4 plant, they could raise the plant's current yield ceiling by as much as 50%. This complex genetic transformation is likely to require many years of research and involve a range of sophisticated techniques, including genetic engineering. The chances of a successful outcome are highly uncertain because the mechanisms and structures involved in C_4 metabolism are complex and the nature of the evolutionary transition from C_3 to C_4 photosynthesis is poorly understood (Barta, 2007; Normile, 2006; Sheehy et al., 2007). So far no positive results have been emerged.

Some improved technologies have certainly increased yields. But in many countries yield growth rates have slowed down over the past decade. The implication of this fact is that the ever-increasing demand for rice can only be met by bringing more land into cultivation, although agricultural land is shrinking due to urbanization; if available, would require drawing more water from surrounding ecosystems to meet the requirements of this 'thirsty' crop.

Several technologies or sets of practices that promise to boost paddy yield per hectare and which require less water have been in use for the past few decades. Some of these offer other economic and environmental benefits as well. Of these practices, SRI is a well-documented methodology that has given demonstrable results in India and other parts of globe.

1.6 System of Rice Intensification: An Option

To meet future needs for food, it is essential to reduce factors used in production, such as land and water, while increasing productivity. One potentially promising technology for yield-enhancement is the System of Rice Intensification (SRI) developed in the mid-1980s in Madagascar developed in an unconventional way and now known and being practiced in more than 50 countries. SRI is a set of improved rice management practices based on several core components with some adjustments to local conditions. The generic agronomic practices for growing transplanted rice, i. e., raising a nursery, transplanting, irrigation, weed management, and nutrient management, are all there in SRI, but there are striking changes made in the way that these are carried out. The rice plants respond in a different, more productive way, resulting in previously unseen crop growth. They are aimed at optimizing the above- as well as below-ground plant growth and development, and improving the performance of the crop as a whole.

SRI typically involves the early transplanting of one or two seedlings (less than 15 days old) per hill, spacing them widely apart (more than 20×20 cm) and subjecting them to alternate wetting and drying (AWD) (Berkhout and Glover, 2011; Stoop et al., 2002). SRI can be practiced with any variety, although seed is usually selected carefully with salt solution. Also, the use of some external inputs is reduced. For example, compared to conventional practices of transplanting bundles of 4–5 seedlings and spacing them less than 20×20 cm apart, SRI requires fewer seedlings. Moreover, in contrast to the conventional irrigation technique of continuous flooding, rice fields are allowed to dry intermittently during the plants' growing period, reducing demand for irrigation water (Rejesus et al., 2011). Along with water-saving, cost-reduction, and resistance to biotic and abiotic stresses (Namara et al., 2004), SRI's potential for high yields has attracted extensive attention.

Although some scientists have debated whether SRI's reputed yield advantages are credible (Dobermann, 2004; Glover, 2011; McDonald et al., 2006; Sheehy et al., 2004; Stoop and Kassam, 2005; Uphoff et al., 2008), recent studies show widespread

A typical view of SRI field

evidence for SRI's apparent yield gains of 50 % or more at a range of sites (Barrett et al., 2004; Berkhout and Glover, 2011; Kassam et al., 2011; Sato et al., 2011; Styger et al., 2011; Takahashi, 2013; Thakur et al., 2010a; Uphoff et al., 2002; Zhao et al., 2009).

1.7 SRI Principles and Practices

The elements of SRI include: transplanting young seedlings, before the start of their 4th phyllochron of growth; reducing plant populations by as much as 80-90% per m^2; converting paddy soils from anaerobic, flooded status to mostly aerobic conditions, by alternate wetting and drying; active soil aeration, with mechanical weeders; and increased soil organic amendments. While some of the practices appear counterintuitive – getting more production from fewer plants, with less water application, and with reduced reliance on chemical fertilizers – the beneficial effects of each practice can be explained and justified scientifically.

The principles of SRI which are fundamental to achieving the expected benefits get translated into certain practices, adapted in their fine points to local conditions. The six principles form the 'SRI Hexagon,' and when adopted together they have a profound effect on the growth of rice plants (Fig. 1).

Fig. 1 Six SRI Principles

Table 1 SRI Principles and practices

S. No.	Principle	Practice
1.	Very young seedlings should be used, to preserve the plant's inherent growth potential for rooting and tillering	10 – 15 day old seedlings with 3 leaves are grown in a raised-bed nursery
2.	Transplanting single seedling per hill should be done quickly, carefully, shallow and skillfully, in order to avoid any trauma to the roots, which are the key to plants' success	Single seedlings are planted with a minimum time interval between uprooting from the nursery and transplanting at a shallow depth (1-2 cm)
3.	Reduce the plant population radically by spacing hills widely and squarely, so that both the roots and canopy have room to grow and can have greater access to nutrients, sunlight, etc.	Planting at grids of either 20 x 20 cm or 25 x 25 cm (or 30 x 30 cm or even wider if the soil is very fertile) using a rope or roller marker to achieve precise inter-plant distances (to facilitate inter-cultivation)
4.	Provide growing plants with sufficient water to meet the needs of roots, shoots and soil biota, but never in excess, so that the roots do not suffocate and degenerate	Up to panicle initiation: Irrigate to 2.5 cm depth after the water ponded earlier disappears and hairline cracks are formed on the soil surface. (Heavy clay soils should not be permitted to reach the cracking stage, but still are issued less water than with usual flooding.) After panicle initiation: Irrigate to a depth of 2.5 cm one day after the water ponded earlier disappears
5.	Active soil aeration improves rice crop growth by benefiting both roots and beneficial aerobic soil organisms.	Inter-cultivation with a mechanical weeder at intervals of 10-12 days, starting 10-12 days after transplanting and continuing until the canopy closes, passing between the rows, and making perpendicular passes across the field
6.	Augmenting organic matter in soils, as much as possible, improves performance of the rice crop, by improving soil structure and functioning and supporting beneficial soil organisms.	Application of cattle manure, green manure, bio-fertilizers, and vermi-compost is recommended. Chemical fertilizer can be used, but it does not have the same beneficial effects on soil systems.

Table 2 SRI vs. Conventional methods and farmer's practices of rice cultivation

Practices	SRI	Conventional recommended practices	Farmer's practices
Seed rate (kg ha-1)	5-7	20-30	50-75
Seedling age (days)	10-15	25-30	25-40
Plant spacing (cm)	20 x 20 or more (square planting)	15 X 10 / 20 X 10	Random
Hill number m-2	16-20	50 – 66	Varying
Seedling number hill-1	Single	2-3	3-6 or more
Water management	Only moist conditions with shallow flooding and sometimes drying of field	Flooding to 5-10 cm depth of water	Continuous flooding to various depth
Weed management	Weeds are turned back into the field by a mechanical hand weeder	Hand weeding twice, at 15 and 35 days after planting, or application of herbicide plus one is hand weeding	2 -3 times hand weeding; herbicide also used by some farmers
Intercultivation	Weeder is used 3-4 times in between rows in both directions (perpendicular)	No	No
Nutrient management	Emphasis on more application of organic manures; sometimes Integrated nutrient management	Integrated nutrient management using organic manures, bio-fertilizers, and chemical fertilizers at recommended levels and timing	Use all recommended manures and fertilizers, but doses and timing vary according to farmers' resources

Source: Thiyagarajan and Gujja, 2012

1.8 Significance of SRI Principles

Significance of various SRI principles is discussed in table 3.

Table 3 SRI principles and their significance

Principle	Significance	Reference
Young seedlings	• Early and greater tillering and root growth • Earlier arrival within a better growing environment in the main field extends the time for tillering • No or lesser transplanting shock	Mishra and Salokhe, 2008; Pasuquin et al., 2008; Menete et al., 2008
Single seedling per hill transplanted at shallow depth	• No competition for nutrients, water and space within a hill • Seed requirements are reduced • Open canopy structure, greater light interception by leaves and lesser shading of lower leaves. This deprives the plant - and especially the roots – of possible supply of photosynthates. • Greater root growth, more cytokinin flux towards shoots, delayed senescence, higher photosynthesis	San-oh et al., 2004; 2006
Wider spacing	• Promote more profuse growth of roots and tillers • More space (below and above ground) per hill for access to nutrients, water and light • Intercultivation with mechanical weeder is made possible	Thakur et al., 2010a
Moist and unflooded water management regime	• Non-hypoxic condition of soil favours root health and functioning, and also supports more abundant and diverse communities of beneficial aerobic soil organisms • No degeneration of roots, which otherwise will be as much as 75% degraded by panicle initiation under flooding • Exposing the soil to sunlight is favourable for warmth • Water savings of up to 40% • Energy saving where water is pumped • Lesser emission of GHGs	Zhao et al., 2009; Satyanarayana et al., 2007; Yang et al., 2004; Jain et al., 2013; Thakur et al., 2011; Suryavanshi et al., 2013

Inter-cultivation	• Churning up of the soil activates the microbial, physical and chemical dynamics • Triggers greater root growth and tillering • Weed biomass is incorporated into the soil as green manure • Weeding costs can be reduced	Satyanarayana et al., 2007
Liberal use of organic manures	• Gives better root growth and activities • More sustained supply of nutrients • Favourable growth of soil biota • Enrichment of soil health	Yang et al., 2004

1.9 Objective of the Study

The objective of this study was to investigate whether SRI practices, could have significant effects on plant growth, development, physiology and subsequently on grain yield and water productivity. A detailed comparison is presented in this report on the performance of rice plants grown with SRI management practices and plants that were raised according to currently-recommended scientific management practices (SMP) which include the flooding of fields.

2. METHODOLOGY

The experiments were conducted over two years at the Deras Farm, Mendhasal in Khurda district, Orissa, India (20° 30’ N, 87° 48’ 10’ E) during the 2008 and 2009 dry season (January-May). A medium-duration rice variety (Surendra, 130-135 days) was planted, which normally gives yields of 3.5-5.0 t ha^{-1} (DRD 2006). The soil of the experimental site was 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 (1.13%). The mineral content was as follows: total nitrogen 0.10%, available P (Olsen) 12 ppm, exchangeable K 0.27 meq/100 g soil, exchangeable Ca 4.8 meq/100 g soil, available S 18 ppm, Zn 12 ppm, and Fe 390 ppm.

2.1 Experiment Details

2.1.1 Experimental design and treatments

The experimental design employed randomized complete block design with five replicates and plot sizes of 20 m x 10 m. Rice was grown under either of the two alternative crop management systems being assessed: the System of Rice Intensification (SRI) with alternate wetting and drying (AWD) water management during vegetative stage; and standard management practices (SMP) with continuous flooding as currently recommended (ICAR, 2006). All plots were surrounded by 50-cm wide bunds to prevent lateral water seepage and nutrient diffusion between plots, followed by 50-cm wide channels for irrigation.

As elaborated by Stoop et al. (2009), any comparison between two systems made up of several different crop management components is subject to confounding effects that will complicate / interfere with the subsequent interpretation of the data. In that context, the results obtained by our group in earlier and different experiments on SRI take on special significance as we evaluated the effects of recommended sets of components rather than just individual components.

2.1.2. Crop management

Organic manure (cow dung mixed with straw) was applied to the entire main field after completion of puddling, leveling and draining off excess water. With both cultivation practices, it was applied at the rate of 5 t ha^{-1} along with chemical fertilizer: urea (80 kg N ha^{-1}), single super phosphate (SSP) (40 kg P2O5 ha^{-1}), and muriate of potash (MOP) (40 kg K_2O ha^{-1}). All 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 SRI recommendation is for organic fertilization in preference to chemical fertilization, but in this evaluation we did not make this practice an additional factor to be assessed; so soil nutrient amendments was not a variable in either amount or form.

Seeds were planted in a nursery, and from there transplanted for SRI plots at 12-days and as single seedlings at a spacing of 20 × 20 cm (25 plants m^{-2}) within 30 min after removal from the nursery, and for SMP plots 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 conoweeder at 10, 20 and 30 days after transplanting (DAT), while the SMP plots had three hand weedings at the same interval.

2.1.3. Irrigation management

SMP plots were kept continuously flooded, being irrigated on alternate days in order to maintain a ponded layer of 5-8 cm depth of water during the entire vegetative stage. In SRI plots, the first irrigation was applied 5 days after transplanting to moisten the field without ponding. A second irrigation was given to the SRI plots on the evening of the 9th day after transplanting at a ponding depth of 2-5 cm, and the next morning a weeding was performed by cono-weeder. Thereafter, the alternate wetting and drying method of irrigation was followed, and irrigation water was applied 3 days after the disappearance of ponded water. After panicle initiation, all plots were kept flooded with a thin layer of water 1-2 cm on the paddies, and all were drained at 15 days before harvest.

2.2 Parameters Measured

2.2.1. Root parameters and xylem exudation rate

Three hills with an average number of panicles (17±1 in SRI and 7±1 in SMP plots) were randomly selected from each replicate at the early-ripening stage for root sampling. Root samples were collected by using an auger 10-cm diameter to remove soil to a depth of 45 cm along with the hill. A uniform soil volume (3,534 cm^3) was excavated to collect root samples from all the treatments. Roots were carefully washed, and various parameters were measured and calculated. Root volume was measured through water displacement method. Root length was measured using Newman's method, and root length density was estimated by dividing total root length by the volume of soil (Yoshida 1981). It was calculated from the following equation:

Root length density = Total root length (cm) / Volume of soil,
Where the roots have been collected (cm^3)

For measurement of xylem exudation rate at the early-ripening stage, three hills with an average number of panicles were randomly selected from each plot replicate. Each stem was cut at 10 cm from the soil surface, and pre-weighed cotton wool packed in a polythene bag was attached with tape to the cut end of 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. Leaf parameters, canopy angle and light interception by the canopy

The youngest leaves of the main stems of 5–10 cm in length were marked for measurement of leaf elongation rate (LER) during the vegetative stage. Leaf length was measured from the tip of the youngest leaf to the ligule of the leaf immediately below. The leaf elongation rate was calculated as the difference in length, divided by the number of days between measurements. Other parameters like average maximum leaf length and leaf width were also recorded. Specific leaf weight (SLW) was calculated by dividing the leaf dry weight by leaf area. Leaf area was measured during the flowering stage using a leaf area meter (LICOR-3100 Area Meter), and leaf area index (LAI) was calculated by dividing 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 vegetative 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:

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

Three hills at flowering stage were selected randomly from each plot for measurements of canopy angle (CA). This was measured with a protractor using the following equation:

CA (in degrees) = 180 - ($\theta_1 + \theta_2$), where θ_1 and θ_2 are the angles of inclination of the outermost tillers from a horizontal orientation on both sides.

2.2.3. Crop growth rate measurements

Plants from three hills randomly selected were collected from each plot during each sampling at 10-day intervals to calculate the crop growth rate (CGR), starting from 30 days after germination (DAG) to 70 DAG. Crop growth rate is the gain in the weight of plants on a unit of land within a unit of time, calculated from the following equation:

CGR = $1/G_A \times (W_2-W_1) / (T_2-T_1)$,
where G_A = ground area, W = weight of crop, and T = time.

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

From each plot, the flag leaf and the fourth leaf (from top) at flowering, middle-ripening and late-ripening stages were marked to measure chlorophyll fluorescence (Fv/Fm and ΦPS II) with a Fluorescence Monitoring System (FMS-2, Hansatech) under both management treatments. 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 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 midday reduction in photosynthesis. After 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 3 × 3 m for each plot were harvested (excluding the border rows) for determination of yield per unit area. Grain yield was adjusted to 14.5% seed moisture content.
Harvest Index (HI) was calculated by dividing dry grain yield by the total dry weight of aboveground parts. Average tiller number and panicle number were 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.

2.2.6. Irrigation water measurements

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

2.3 Data Analysis

All data were statistically analyzed using analysis of variance (ANOVA) technique as applicable to randomized block design (Gomez and Gomez, 1984). The significance of the treatment effect was determined using F-test, and to determine the significance of the difference between two treatments means, least significant difference (LSD) was estimated at the 5% probability level.

The data set for all the parameters was statistically analyzed considering year as a source of variation in addition to the treatment (practice). The main effect of year and the interaction effects of year × practice were not significant at $P < 0.05$ for most of the parameters, so the data reported in this paper are averages for two years of trials.

3. RESULTS

3.1 Rice Plant Morphology under SRI

3.1.1 Root growth

The most important morphological difference between rice plants grown under SRI and SMP was observed in their root growth, volume and density. Root growth was measured at early ripening stage, a stage when active grain-filling starts in the rice crop. Roots per hill were nearly twice as heavy, were considerably deeper, and more than double the length and volume in SRI hills compared to SMP hills (Table 4). Similarly root volume was also more than double in unit area terms under SRI vs. SMP management. Root dry weight was not significantly different on a per unit area basis, mainly because of the greater number of hills in SMP plots. However, root length density was significantly greater in SRI than SMP.

Table 4 Effects of rice management practices on root depth, root dry weight, root volume, root length and root length density at early-ripening stage of development

Management practice	Root depth (cm)	Root dry weight (g hill^{-1})	Root dry weight (g m^{-2})	Root volume (ml hill^{-1})	Root volume (ml m^{-2})	Root length (cm hill^{-1})	RLD (cm cm^{-3})
SRI	33.5	12.3	306.9	53.6	1340.0	9402.5	2.7
SMP	20.6	5.8	291.8	19.1	955.0	4111.9	1.2
LSD$_{.05}$	3.5	1.3	NS	4.9	180.1	712.4	0.2

SRI: System of Rice Intensification, SMP: standard management practice of flooded rice, RLD: Root length density

3.1.2 Plant height and tillering

Roots of rice plants grown under conventional practices (left) and SRI (right)

Clearly visible differences in plant morphology were observed between SRI plants and conventionally-grown flooded rice with standard management practice (SMP) at the critical early ripening stage. SRI plants were 22% and 24% taller in plant and culm height, respectively, compared to SMP plants (Table 5). SRI hills had double the number of tillers than SMP hills, but there was no significant difference in tillers per unit area, mainly due to the greater number of hills per unit area under SMP. Average tiller perimeter was significantly greater (38% more) in SRI compared to SMP plants.

Table 5 Effects of rice management practices on morphological characteristics at early-ripening stage of development

Management practice	Plant height (cm)	Culm height[a] (cm)	Ave tiller number (hill^{-1})	Tiller number (m^{-2})	Ave. tiller perimeter[b] (cm)
SRI	124.2	84.0	18.3	450.1	2.9
SMP	101.4	67.5	8.9	441.2	2.1
LSD$_{.05}$	8.1	4.3	3.5	NS	0.3

SRI: System of Rice Intensification, SMP: standard management practice of flooded rice

[a] Length between plant base and the panicle neck node

[b] Tiller perimeter includes culm and leaf sheath at 10 cm height above the ground

In SRI plots, the number of tillers per hill varied from 12-34 (average: 18.3 tillers hill^{-1}). However, in SMP plots the number ranged from 5-18 (average: 8.9 tillers hill^{-1}). The lowest tillering SRI plant almost matched the highest tillering SMP plant. On an area basis, on the other hand, tiller number was found to be somewhat lower in SRI than in the SMP plots. However, percentages of effective tillers were higher in SRI than SMP plots. The phyllochron study showed that in SRI individual hills reached the stage of 10th phyllochron with an average number of tillers 28 (Fig. 2). In SMP plots, individual hills only reached up to 8th phyllochron before onset of flowering stage and able to produce only 8-10 tillers per hill. After 60 days of germination of seed, there were no further changes in number of tillers in SMP hills indicate that these plants started experiencing constraints in terms of light, nutrients and space contrary to SRI hills (Table 6).

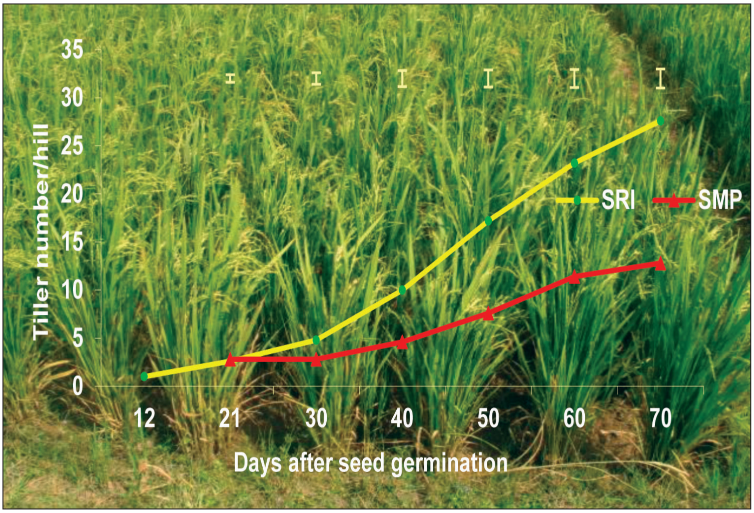

Fig. 2 Changes in tiller number per hill in SRI and SMP methods. Solid squares and solid triangles represent SRI and SMP, respectively.

Tillering in rice crop grown under SRI (left) and conventional practices (right)

Table 6 Comparison between numbers of phyllochrons[a] completed under SRI and SMP

Cultivation method	10 DAG	30 DAG	40 DAG	50 DAG	60 DAG	70 DAG
SRI	Transplanted <4th phyllochron	6th Phyllochron	7–8th phyllochron	8-9th phyllochron	9th phyllochron	10th Phyllochron
SMP	In Nursery	Transplanting shock	6th Phyllochron	7th Phyllochron	8th Phyllochron	8th Phyllochron

[a] Phyllochron: The period of time in which one or more units of tiller, leaf and roots, each unit constituting a phytomer, emerges from the plant's meristematic tissue as described by Nemoto et al. (1995).

DAG: Days after germination of seed.

3.1.3 Leaf morphology, growth, and canopy structure

At flowering stage, the number of leaves per hill and per unit area in the SRI treatments was significantly higher than in SMP (Table 7). SRI hills had more than twice the number of leaves compared to hills under SMP plots. On average, SRI leaves were significantly longer (35.5%) and wider (35.8%) than SMP leaves. Similarly, average length and width of flag leaves were also significantly larger in SRI plants compared to SMP plants. The greater number of larger leaves in SRI crops resulted into significantly higher leaf area index (LAI) compared to SMP rice plants. Also, the leaves of SRI plants had higher specific leaf weight (SLW), another morphological difference.

Table 7 Effects of rice management practices on morphological characteristics of leaves at flowering stage of development

Management practice	Leaf number (hill^{-1})	Leaf number (m^{-2})	Ave. leaf length (cm)	Ave. leaf width[a] (cm)	Ave. flag leaf length (cm)	Ave. flag leaf width[a] (cm)
SRI	79.8	1997.6	65.25	1.82	39.45	2.10
SMP	35.6	1766.5	48.14	1.34	30.27	1.66
LSD$_{.05}$	15.8	229.4	6.09	0.21	4.49	0.31

[a] Maximum width of each leaf from hill was measured

Of particular interest was the difference in canopy structure when evaluated at the flowering stage. SRI hills had a significantly greater canopy angle than SMP hills (Table 8). In SRI plants, new tillers emerged at a greater angle from the vertical than in SMP plants. New tillers in the latter emerged more upright within clumps of plants, while the SRI tillers emerging in single plants were not spatially constrained. This gave SRI hills a more open plant structure, with more and better exposure to sunlight. This could be attributed to the shallower planting (1-2 cm) of SRI rice as well as to there being less crowding of SRI plants. Also, we found that the angle between the leaf blade and the stem/tiller, flag leaf and panicle axis was lesser in SRI plants than SMP plants. This meant that SRI leaves were more erect as compared to SMP (Table 9).


Open Canopy structure of rice hills under SRI

Table 8 **Effects of rice management practices on leaf area index (LAI), specific leaf weight (SLW), and canopy angle at flowering stage of development**

Management practice	LAI	SLW (mg cm^{-2})	Canopy angle (°)
SRI	3.95	5.50	33.1
SMP	2.60	4.89	17.8
LSD$_{.05}$	0.28	0.34	3.6

Table 9 Comparison of leaf inclination and canopy angle under SRI and SMP at the middle ripening stage

Cultivation method	1st leaf (flag leaf)[a]	2nd leaf	3rd leaf	4th leaf	5th leaf
SRI	7.1	5.0	7.5	11.1	16.4
SMP	9.3	7.6	9.8	13.8	20.1
$LSD_{.05}$	0.8	0.6	0.8	1.2	1.7

[a] Angle between flag leaf and panicle axis

3.2 Crop growth and physiological responses under SRI

3.2.1 Xylem exudation rates

The amount of xylem exudates transported from roots toward the shoot was significantly more in SRI plants at the early ripening stage, both per hill and per unit area (Table 10). The amount of exudates transported from roots was 209% greater in SRI hills than in SMP hills. Similarly, the rate at which these exudates were transported was also significantly faster in SRI hills, 3 times more than in the SMP hills or land area.

Table 10 Effects of rice management practices on xylem exudation rates at early-ripening stage of development

Management practice	Amount of exudates per hill (g $hill^{-1}$)	Amount of exudates per area (g m^{-2})	Rate per hill (g $hill^{-1}$ h^{-1})	Rate per area (g m^{-2} h^{-1})
SRI	7.61	190.25	0.32	7.93
SMP	2.46	122.95	0.10	5.12
LSD.05	1.45	39.72	0.06	1.66

SRI: System of Rice Intensification, SMP: standard management practice of flooded rice

3.2.2 Crop growth rate (CGR)

This was measured during the vegetative stage of crops grown under both management practices. Up to 60 days after germination, CGR was higher in the crop grown under SMP than SRI methods. However, beyond 60 DAG, crop growth rate in SMP declined compared to what was observed with SRI (Fig. 3). In the SRI crop, CGR showed a continuously increasing trend throughout the vegetative stage of growth as a result of unimpeded tillering. Directly linked to this tillering is a continued root development (through adventitious roots) which under an AWD soil moisture regime remained active, while the roots under continuous flooding degenerated significantly.

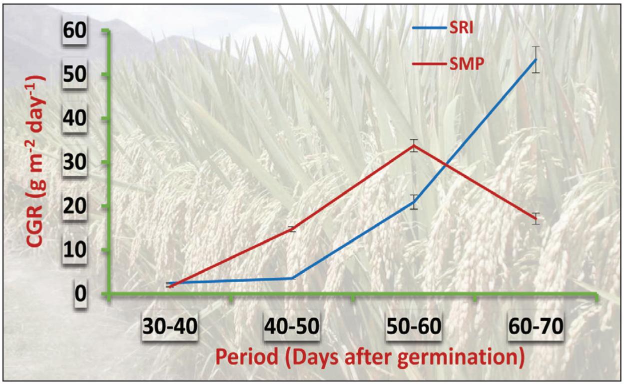

Fig. 3 Changes in crop growth rate (CGR) for rice plants during their vegetative stage when grown with SRI and SMP practices. Vertical bars represent SEm ± (n=10)

3.2.3 Mean leaf elongation rate (LER)

The parameter of leaf elongation rate (LER) was significantly affected by management practices. Mean LER, measured between 40 to 70 days after germination during the vegetative stage, was significantly higher in rice plants grown under SRI than SMP (Fig. 4). SRI leaves elongated at a rate 34% greater than did SMP leaves.

Fig. 4 Different responses to rice crop management practices for mean leaf elongation rate (LER) at vegetative stage (40-70 DAG). Vertical bars represent SEm ± (n=10). LSD.05 was 0.70

3.2.4 Light interception

During the initial growth stages (up to 40 DAG), the SMP canopy intercepted more solar radiation than did the SRI canopy (Fig. 5). At 50 DAG, there were no significant differences in light interception. Then, beyond 50 DAG, light interception in SRI plots was significantly more than in the SMP plots. At the panicle initiation stage, light interception reached 89% in SRI plots, while it was only 78% in SMP canopies at this stage, giving SRI plants a 15% advantage on this parameter.

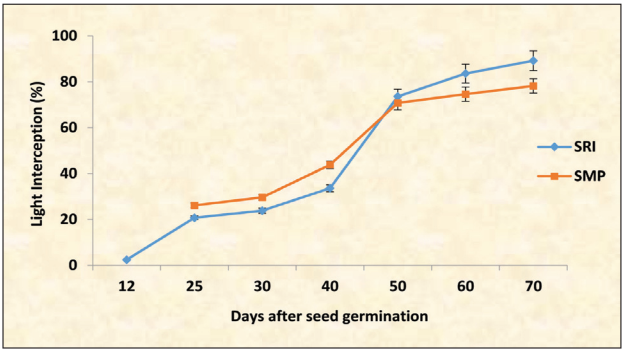

Fig. 5 Changes in the light interception by the canopy during vegetative stage in rice plants grown with SRI and SMP practices. Closed and open circles represent SRI and SMP management, respectively. Vertical bars represent SEm ± (n=10)

3.2.5 Leaf chlorophyll content, fluorescence, and photosynthetic 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 SMP plants at all the three stages of development evaluated, i.e., flowering (FL), middle-ripening (MR), and late-ripening (LR) stages (Fig. 6).

Under both cultivation practices, these parameters decreased with the stage of developmental progress. However, in SRI leaves, leaf chlorophyll content decreased by only 36% between FL and LR stages. The parallel decrease in the leaf chlorophyll content of SMP plants was 49%, more than one-third greater.

Both maximum and actual quantum efficiency, an indicator of light utilization capabilities of the leaf for light reaction of photosynthesis, showed a greater decrease in SMP leaves than in SRI leaves at LR stage compared to FL stage. In SMP plants, the leaf photosynthesis rate at late ripening, compared to flowering, was 80% lower, while in SRI plants, there was only about half as much decline (43%).

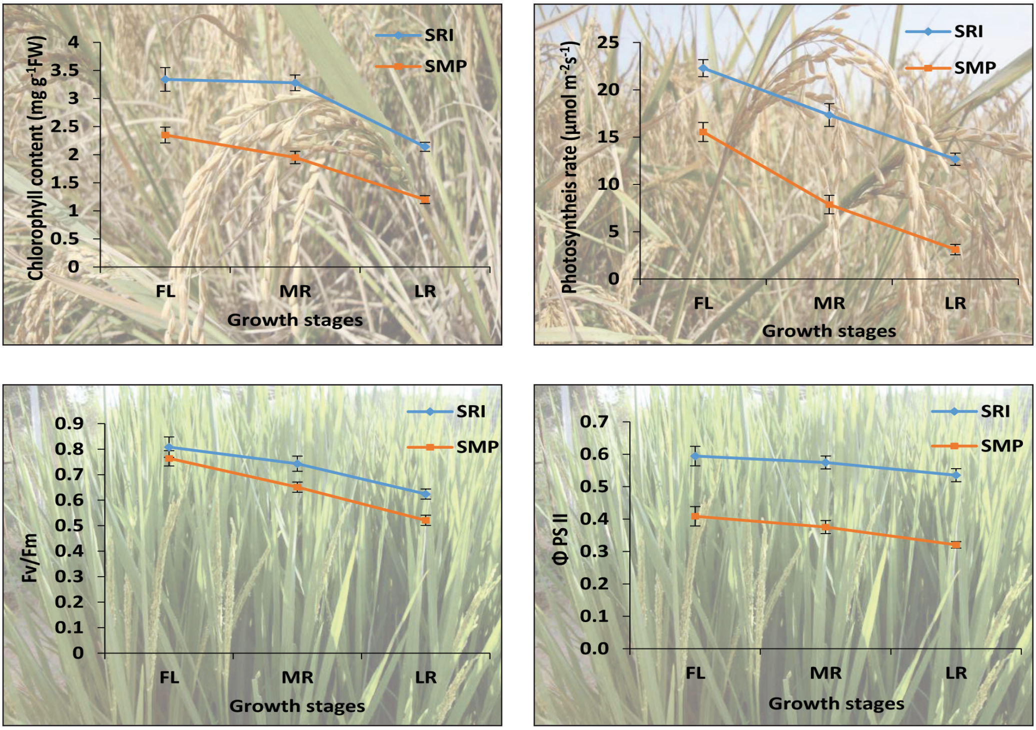

Fig. 6 Changes in leaf chlorophyll content, chlorophyll fluorescence quantum yield (Fv/Fm and Φ PS II), and photosynthesis rate at different growth stages (FL: Flowering stage; MR: Middle-ripening stage; LR: Late-ripening stage) in SRI and SMP. Vertical bars represent SEm ± (n=10)

From their initial growth to the late ripening stage, SRI plots appeared greener than the conventionally-managed plots. At the middle ripening stage, SRI flag leaves had higher Chl *a*, Chl *b* and total Chlorophyll content than did those in SMP plants, as well as a higher Chl *a/b* ratio (Table 11). At the middle ripening stage, the maximum fluorescence efficiency (Fv/Fm) and the actual fluorescence efficiency (ΦPS II) of flag leaves were also significantly higher in the SRI crop compared to the SMP crop. The reduction in fluorescence efficiency from maximum to actual was more in the leaves of the crop grown under SMP compared to SRI. At the middle ripening stage, there were significant differences in flag leaf photosynthesis, internal CO_2 concentration, and transpiration rate

Table 11 **Comparison of chlorophyll content, fluorescence, transpiration rate, net photosynthetic rate, stomatal conductance, and internal CO_2 concentration in SRI and SMP at middle ripening stage**

Parameters	Cultivation method		$LSD_{.05}$
	SRI	SMP	
Chlorophyll a (mg g^{-1}FW)	2.18	1.43	0.12
Chlorophyll b (mg g^{-1}FW)	1.13	0.88	0.06
Total chlorophyll (mg g^{-1}FW)	3.31	2.31	0.13
Chlorophyll a/b ratio	1.93	1.63	0.22
Fv/Fm ratio	0.811	0.714	0.014
Φ PS II	0.621	0.469	0.021
Transpiration (m mol m^{-2} s^{-1})	6.17	8.13	0.24
Leaf temperature (°C)	34.14	33.14	ns
Net photosynthetic rate (µ mol m^{-2} s^{-1})	22.19	13.14	1.52
Stomatal conductance (m mol m^{-2} s^{-1})	421.66	487.91	28.17
Internal CO_2 concentration (ppm)	301.7	351.0	12.1
Instantaneous WUE (µ mol / m mol)	3.6	1.6	0.8

between SRI and SMP. Net photosynthesis rate was significantly higher in SRI plants than in SMP plants. However, SMP rice crop had higher transpiration rate than SRI crop. The ratio of photosynthesis to transpiration (instantaneous water-use efficiency) was accordingly higher in SRI plants compared to SMP crops (3.6 versus 1.6 µ mol / m mol).

3.3 Yield components and yield performance under SRI

Average number of panicles per hill was significantly greater (more than double) in SRI hills (average: 16.9 hill^{-1}; range: 12-30 hill^{-1}) than in hills under SMP (average: 6.9 hill^{-1}; range: 4-12 hill^{-1}). Similarly, the number of panicles per unit area was also significantly higher under SRI (439.5 panicles) than SMP (355.2 panicles) (Table 12). Further, the average panicle length in SRI (22.5 cm) was higher than panicles in SMP (18.7 cm) (significant at $p < 0.05$). The longer SRI panicles carried nearly 40% more number of grains compared to panicles obtained from SMP, and the percentage of ripe grains and 1000-grain weight were also significantly higher in SRI plants than SMP plants.

Table 12 Effects of rice management practices on yield-contributing characters

Management practice	Ave. panicle number hill^{-1}	Panicles (m^{-2})	Ave. panicle length (cm)	Spikelet number/ panicle	Filled spikelets (%)	1000-grain weight (g)
SRI	16.9	439.5	22.5	151.6	89.6	24.7
SMP	6.9	355.2	18.7	107.9	79.3	24.0
LSD.05	3.5	61.6	2.3	12.9	5.1	0.2

Frequency distribution pattern showed that SRI plots had the more number of longer panicles, however, SMP plots had more number of shorter panicles. SRI plots had the highest number of panicles per unit area of land that were 23.1–24.0 cm long. This was different from SMP plots whose highest number of panicles was 18.1–19.0 cm long (Fig. 7). Most of the panicles (66%) in SRI were 20.1 cm to 24.0 cm in length, while most SMP panicles (66%) were 15.1 cm to 20.0 cm long. It was noted that, with SRI, no panicle was <15 cm length; in contrast, no SMP panicles were >25 cm long.

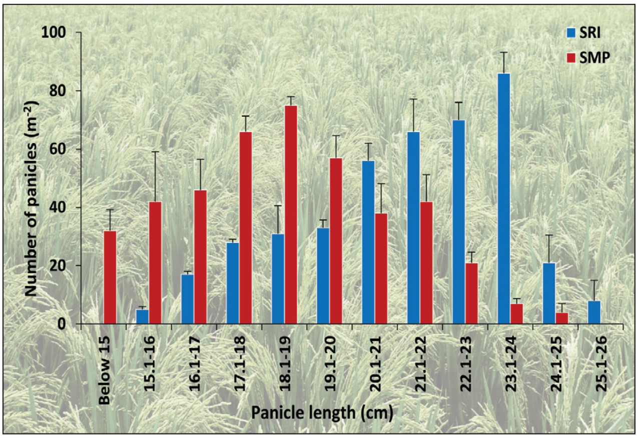

Fig. 7 Frequency distribution of panicle length m^{-2} in SRI and SMP. Black and white bars represent SRI and SMP, respectively.

The relationship between panicle length and grain number in SRI and SMP is shown in Fig. 8. With SRI management, each centimetre of increase in panicle length could accommodate 12 grains, whereas with SMP, only 6 grains could be accommodated by each additional centimetre. The alternative sets of management practices thus produced a difference in the branching of panicles, so that the structure of SRI panicles could accommodate more grains.

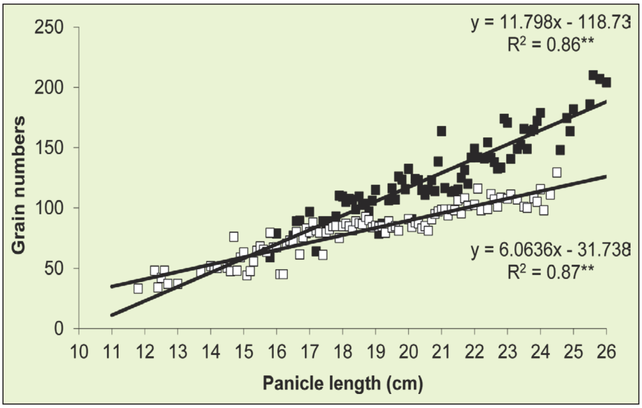

Fig. 8 Relationships between the panicle length and grain number with SRI (n = 81) and SMP (n = 103). Black and white squares represent SRI and SMP, respectively.

The significant improvement in yield components resulted in 48% higher grain yield under SRI management than from crop grown under SMP (Table 13). The usual yield of the tested variety under local conditions in Orissa has been previously reported to range from 3.5 to 5 t ha^{-1}. In these trials, while SMP achieved a yield of 4.4 t ha^{-1}, the SRI yield was 6.5 t ha^{-1}. The straw weight per unit area was, on the other hand, significantly greater in SMP. This resulted in a significant decrease in Harvest Index as compared with the SRI plots.

Table 13 Effects of rice management practices on grain yield, straw weight, and harvest index

Management practice	Grain yield (t ha^{-1})	Straw weight (t ha^{-1})	Harvest index
SRI	6.51	7.28	0.47
SMP	4.40	9.17	0.32
LSD$_{.05}$	0.26	1.19	0.04

3.4 Water productivity and water savings under SRI

During the two cropping seasons (January to May) of 2008 and 2009, rainfall received was 185.5 and 70 mm, respectively. The irrigation method used for SRI, i.e., alternate wetting and drying (AWD) during the vegetative stage of the crop, demonstrated significantly higher water productivity (0.68 g litre^{-1}) compared to continuously-flooded SMP rice (0.36 g litre^{-1}) (Table 14).

Table 14 Effects of rice management practices on water productivity and its savings during 2008 and 2009

Year	Rainfall (×10^4 litres / ha)		Irrigation applied (×10^4 litres / ha)		Total water consumed (×10^4 litres / ha)		Water productivity (g/ litre)		Water saving with SRI (×10^4 litres / ha)
	SRI	SMP	SRI	SMP	SRI	SMP	SRI	SMP	
2008	185.5	185.5	727.6	1,017.5	913.1	1,203.0	0.72	0.36	289.9 (24.1)
2009	70.0	70.0	920.4	1,172.4	990.4	1,242.4	0.65	0.36	252.0 (20.3)
Average	127.8	127.8	824.0	1,094.9	951.8	1,222.7	0.68	0.36	270.9 (22.2)

SRI: System of Rice Intensification, SMP: standard management practice of flooded rice
Values in parentheses are percent water saving in SRI compared to SMP

On an area basis, the AWD method of irrigation saved 22.2% water compared to what was required for continuously-flooded SMP rice. It was observed that AWD water saving was due mostly to reduction in seepage and percolation losses. It was also calculated that 1,463 litres of water were required to produce 1 kg of rice through SRI methods, while 2,778 litres of water were needed for producing the same amount of rice by continuously-flooded SMP rice cultivation.

4. DISCUSSION

System of rice intensification method aims to make irrigated rice cultivation more sustainable and profitable, as it not only enhances grain yield and net income, but also save considerable amount of capital, seed, and most importantly, water (Uphoff, 2003). SRI practices include transplanting of young single seedlings at a wider spacing, use of a mechanical weeder to control weeds and for aeration of the soil, and intermittent irrigation (Stoop et al., 2002). In contrast, prevailing methods of rice cultivation involve use of older seedlings at closer spacing and continuous flooding (Stoop et al., 2009). SRI recommendations also include considerable organic soil amendments, but this practice was not evaluated here.

Several experiments conducted during recent years on irrigated rice crop growth have supported the respective practices associated with SRI management. There is an improvement in tillering, root development, rubisco content, and cytokinin levels when single seedlings per hill are transplanted over transplanting three seedlings per hill under conventional flooded conditions (San-oh et al., 2006). Transplanting of younger seedlings is advantageous for early crop establishment and by avoiding/minimizing of transplanting shock thus achieving higher grain yields (Pasuquin et al., 2008). Wide spacing reduces inter-plant competition for nutrients, water, light, and air, which accounts for a significant enhancement in individual hill performance under SRI (Thakur et al., 2010a), largely due to an unrestrained tillering process and the associated/ additional root development.

Alternate wetting and drying (AWD) is considered as an effective water-saving technology in rice production. Study by Zhang et al. (2009a) showed that moderate AWD not only saves water, but also increases grain yield by 11%. Our results showed AWD irrigation method in combination with other SRI practices saving 22% of water while water productivity was substantially improved as compared with continuously flooded rice (Table 14). At the same time, AWD with associated practices enhanced yield by 48% under on-station controlled trials (Table 13). Yield enhancement and water savings through SRI practices has also been reported in the countries as diverse as China (Zhao et al., 2009), Cambodia (Ly et al., 2012), Gambia, India (Senthilkumar et al., 2008; Sinha and Talati, 2007; Thakur et al., 2010b), Indonesia (Sato and Uphoff, 2007), Japan (Chapagain and Yamaji, 2010), Korea (Choi et al., 2013), Kenya (Ndiiri et al., 2013), Madagascar (Tsujimoto et al., 2009), Myanmar (Kabir and Uphoff, 2007), and Sri Lanka (Namara et al., 2008).

How could reduced water application under SRI methods lead to higher rice yield? This is what we wanted to assess in this evaluation as it would create a strong incentive for farmers to adopt water-saving methods. In this study, we documented significant changes in the morphological and physiological characteristics of SRI plants in comparison to flooded rice.

Root studies of the crop showed a differential pattern of growth in SRI and SMP methods. The effective root depth, total root length, and dry weight per hill recorded at grainfilling stage were significantly better in SRI than for a flooded SMP crop. On a unit area basis, however, root dry weight was not significantly different. The proportion of roots that were brown or black (non-functional and decayed or decaying) was observed to be more in continuously flooded SMP plots, compared with SRI. Kar et al. (1974) found that roots in aerobic soil senesce much less, more slowly; this is correlated with the observable differences in root degradation, although that association was not examined in this study. Chapagain and Yamaji (2010) have reported that before the flowering stage, the average proportion of whitish (functional) and black (non-functional) roots was 74:26 under SRI management; conversely, in continuously flooded plots it was 46:54.

SRI practices not only induced greater root growth, but also enhanced root activity. This was evident from the greater xylem exudation rates in our study (Table 10). Another impact of greater and deeper root systems in AWD irrigated rice is enhanced nutrient uptake (Yang et al., 2004; Zhang et al., 2009a); continuously submerged paddy fields, on the other hand, impair root development thus affecting nutrient uptake negatively (Olaleye et al., 2001; Sahrawat, 2000; Imbellone et al., 2001). Due to AWD irrigation and use of weeder, it is expected that soils under SRI method remains in more aerobic condition than paddy soil under completely submerged conventional method. Therefore, probability of existing nitrogen in nitrate (NO_3-) form becomes greater under SRI than flooded condition. Aerobic soil environments realized with SRI management might be favorable for nitrification as well as for the expansion of rhizosphere area, which could enhance nitrate uptake and boost the yield potential of rice (Toriyama and Ando, 2011). Jain et al. (2013) found higher amount of nitrate nitrogen under SRI field and greater ammonical (NH_4+) nitrogen in soil under flooded rice. Kirk (2001) reported synergistic effect on crop growth in presence of both NH_4 and NO_3 forms and concluded that co-provision of NH_4 and NO_3 enhances total N-uptake. Also, NO_3 enhances expression of genes for NH_4 transporters and its assimilation (Zhao et al., 2008). Recently, it was found that at low nitrate concentration, NRT1.1 transporter appears to supply auxin to the epidermis flow and moving auxin away from the lateral root primordium tip led to Inhibition of lateral roots outgrowth. However, at high nitrate conditions, NRT1.1-dependent auxin transport are inhibited, reduce contribution to the auxin flow in the epidermis; more auxin accumulates at the tip which stimulates lateral root outgrowth (Krouk et al., 2010).

Higher root growth and activity under SRI relates to increased root oxidation activity and root-sourced cytokinins (Zhang et al., 2009a), which are believed to play a major role in promoting cell division thereby delaying senescence of the leaves (Yang et al., 2002; Soejima et al., 1995; del Pozo et al., 2005; Ookawa et al., 2004). Consequently, higher levels of leaf chlorophyll content (delayed senescence) are maintained also so that the fluorescence efficiency and photosynthetic rate can be increased in SRI compared with flooded SMP rice (Fig. 6). The improved root and shoot growth under SRI rice will have contributed directly to larger panicles (more spikelets per panicle), better grain setting (higher percentage of filled grains), and heavier individual grains (higher 1000 grain weight). Zhang et al., (2009b) have also reported that higher grain yield in the ‘‘super’’ rice varieties (Liangyoupeijiu and Huaidao 9) was attributable to improved root and shoot growth, which contributed to the larger sink size (total number of spikelets). SRI practices enhance the plants’ growth and tillering ability and improve plant/culm height and strength of tillers (greater tiller perimeter). Tillering ability in rice has a close relationship with the number of phyllochrons completed before entering the reproductive stage (Nemoto et al., 1995; Stoop et al., 2002).

SRI plants, due to their early establishment, only suffered minimally from transplanting shock; the subsequent favorable growing conditions allowed the plants to complete a greater number of phyllochrons before the onset of anthesis, while producing a greater number of strong tillers and larger root systems than did SMP plants (Thakur et al., 2010b). Conversely, SMP plants appear to be constrained by their competition for nutrients, space and light during their later stages of vegetative growth, which was illustrated by the slowing down of crop growth rate (CGR) beyond 60 days after germination (Fig. 3).

Number and size of leaves were significantly increased in SRI plants compared with SMP at the flowering stage which led to a higher leaf area index (LAI) than in SMP (Tables 7 and 8). The extensive root systems developed by SRI plants enhanced water and nutrient uptake, resulting in greater leaf elongation rates (LER), which may have contributed for larger leaf size. Earlier reports have also showed LER to be significantly enhanced in rice grown under just-saturated soil culture compared to a flooded water regime (Nguyen et al., 2009). The higher specific leaf weight (SLW) in SRI plants indicated thicker leaves compared to the leaves on rice plants grown under SMP. SMP rice plants had a more compact structure, with tillers that were more vertical/less horizontal. In contrast, SRI plants had more open architecture (greater canopy angle), with tillers splayed out more widely and covering more ground area. Greater LAI and a more favorable canopy structure facilitate higher light interception in the SRI crop beyond 50 DAG (Fig. 5).

This study also showed that SRI leaves had higher light utilization capacity (Fv/Fm and ΦPS II) and a greater photosynthetic rate, especially during the reproductive and ripening stages of the crop (Fig. 6). Actively photosynthesizing leaves ensure a sufficient supply of assimilates to the roots for their development and longevity, maintaining active root functioning.

At the same time, high root metabolic activity supports a high photosynthetic rate by supplying a sufficient amount of nutrients to the shoot/leaf (Samejima et al., 2004; Yang et al., 2004; Mishra et al., 2006; Zhang et al., 2009a). This interdependent relationship has been referred to as the root-shoot interaction (Samejima et al., 2004), and SRI practices have a substantial effect on such root-shoot interaction.

Other reports (Menete et al., 2008; Thakur et al., 2013, 2014) as well as the present findings have showed significant improvements in per-hill performance under SRI, in terms of morpho-physiological characteristics, with resulting enhancement of grain yield. However, since yield is assessed by performance per unit area, greatest productivity is achieved by optimizing the number of plants m^{-2} without compromising individual plant performance for maximizing grain yield.

A proposed model

From our review and interpretation of results associated with SRI practices, we propose a model (Fig. 9) to describe some of the known morphological and physiological changes responsible for greater grain yield of rice plants grown under SRI. The model postulates that in the SRI method of cultivation various practices, like transplanting young single seedling at wider spacing, AWD irrigation, compost use, and use of mechanical weeder (cultivator) leads to rice plants with greater and robust roots with more activity. Greater root development is beneficial for higher microbial activity, water and nutrient uptake as there is more root exudation into the rhizosphere and more capacity for acquisition of growth factors. Robust root growth also favours cytokinin synthesis, thereby enabling more cytokinin flux from the root to the shoot, resulting in delayed senescence of leaves and more photosynthetic activity (i.e., more rubisco) with greater N and chlorophyll content. Also, enhanced photosynthetic rate of lower leaves supplies greater carbohydrates towards root to support their activity, an important phenomena during grain-filling stage of crop. On the other side, Greater and faster tillering in SRI plants results into more leaf numbers with greater size of leaves and higher leaf area index (LAI). Open canopy structure (to cover more ground area) with erect leaves (minimizing shading of lower leaves) coupled with higher LAI resulting in greater light interception at later phase of vegetative growth. These phenotypic alterations of SRI plants with improved beneficial physiological processes responsible for production of longer panicles with more grains and better grain filling, ultimately result in more highly productive hills under SRI practice.

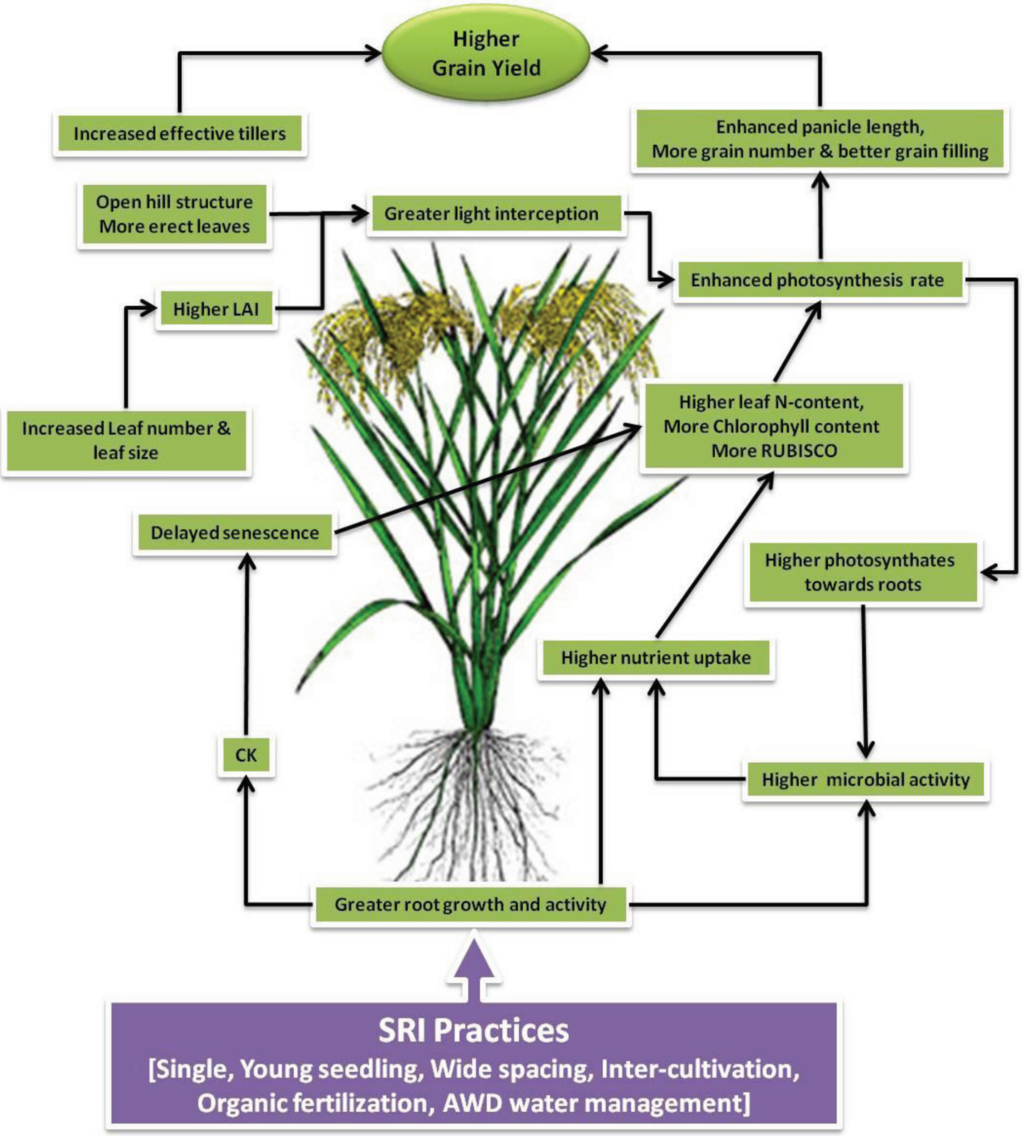

Fig. 9 A schematic model showing factors that may be responsible for higher grain yield of rice plant grown under SRI management practices. (CK: Cytokinins; LAI: Leaf area index; RUBISCO: Ribulose-1,5-bisphosphate carboxylase/ oxygenase)

5. CONCLUSIONS

Essentially, SRI practices create more favorable soil-water-plant-atmosphere relationships than are achieved under conventional wetland rice production with continuously flooded fields and hypoxic soil conditions. These practices should have positive impacts on beneficial soil biota as well as on rice plant roots and canopies. This experiment showed the impact of SRI practices on crop performance and water productivity with enhancement in land productivity (yield per unit of land) compared to currently favored cultivation methods with inundated rice paddies.

The improvement in grain yield under SRI practice was mainly due to improved morphology and physiological features of the rice plant below and above the ground surface. SRI practices improve the growth of roots and their activity, favoring water and nutrient uptake, which resulted into a delayed senescence of the leaves and a higher photosynthetic rate.

All of these processes can be enhanced by supportive bacteria, fungi, and other beneficial soil organisms, but these relationships were not assessed in this study. Against the backdrop of water scarcity with concomitant pressure to produce more grain-more crop per drop-SRI with AWD irrigation is a promising option for rice growers, more attractive than other, presently available methods of rice cultivation.

Acknowledgements

Authors acknowledge the help and cooperation of Dr. M.S. Behera, Farm Manager and Technical Assistants of Experimental Farm and Laboratory for carrying out field and laboratory experiments. Authors are thankful to ICAR, Govt. of India for providing financial support in carrying out this research work under in-house research projects. Authors also acknowledge Prof. Norman Uphoff, Cornell University, Ithaca, USA and Dr Willem A. Stoop, former staff member and consultant for West African Rice Development Association (WARDA), for offering useful comments while preparing the draft of this bulletin.

References

Atlin, G. N., Lafitte, H. R., Tao, D., Laza, M., Amante, M. and Courtois, B. (2006). Developing rice cultivars for high-fertility upland systems in the Asian tropics. *Field Crops Res.* 97: 43-52.

Barrett, C. B., Moser, C. M., McHugh, O. V. and Barison, J. (2004). Better technology, better plots, or better farmers? Identifying changes in productivity and risk among Malagasy rice farmers. *American Journal of Agricultural Economics,* 86(4): 869-888.

Barta, P. (2007). *Feeding Billions, A Grain at a Time.* The Wall Street Journal, New York City (online).

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

Belder, P., Bouman, B.A.M. and Spiertz, J.H.J. (2007). Exploring options for water saving in lowland rice using a modeling approach. *Agric Syst* 92:91-114

Berkhout, E. and Glover, D. (2011). The evolution of the system of rice intensification as a socio-technical phenomenon: A report to the Bill & Melinda Gates Foundation. Wageningen: Wageningen University and Research Centre.

Bouman, B.A.M. (2007). A conceptual framework for the improvement of crop water productivity at different spatial scales. *Agric Syst* 93:43-60

Bouman, B.A.M., Peng, S., Castaneda, A.R. and Visperas, R.M. (2005). Yield and water use of irrigated tropical aerobic rice systems. *Agric Water Manag* 74:87-105

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

Bouman, B.A.M., Lampayan, R.M. and Tuong, T.P. (2007). Water management in irrigated rice: Coping with water scarcity. International Rice Research Institute, Los Baños, Philippines 54 p.

Chapagain, T. and Yamaji, E. (2010). The effects of irrigation method, age of seedling and spacing on crop performance, productivity and water-wise rice production in Japan. *Paddy Water Environ* 8:81–90.

Choi, J.D., Park, W.J., Park, K.W. and Lim, K.J. (2013). Feasibility of SRI methods for reduction of irrigation and NPS pollution in Korea. Paddy Water Environ 11:241-248.

Dawe, D., Barker, R. and Seckler, D. (1998). Water supply and research for food security in Asia. In ''Proceedings of the Workshop on Increasing Water Productivity and Efficiency in Rice-Based Systems,'' July 1998, International Rice Research Institute, Los Banos, Philippines.

del Pozo, J.C., Lopez-Matas, M.A. and Ramirez-Parra, E. (2005). Hormonal control of the plant cell cycle. *Physiol Plant* 123:173–183.

Doberman, A., Dawe, D., Roetter, R.P. and Cassman, K.G., 2000. Reversal of rice yield decline in a long-term continuous cropping experiment. *Agron. J.* 92:633–643.

Dobermann, A. (2004). A critical assessment of the system of rice intensification (SRI). *Agric Syst.* 79:261–281.

DRD (2006). Rice varieties released/notified during 1996–2005. Directorate of Rice Development, Department of Agriculture and Co-operation, Ministry of Agriculture, Govt. of India, Patna

Fageria, N.K. (2007). Yield physiology of rice. *J Plant Nutr* 30:843–879.

Farooq, M., Kobayashi, N., Wahid, A., Ito, O. and Shahzad M. A. Basra (2009). Strategies for producing more rice with less water. *Advances in Agronomy* 101:351-388.

Glover, D. (2011). The system of rice intensification: time for an empirical turn. *NJAS- Wageningen Journal of Life Sciences*, 57(1):217-224.

Gomez, K.A. and Gomez, A.A. (1984). Statistical Procedure for Agricultural Research. John Wiley, New York, USA pp.680

Hiscox, J.D. and Israelstam, R. (1979). A method of extraction of chlorophyll from leaf tissue without maceration. *Can J Bot* 57:1332-1334.

ICAR (2006). *Handbook of Agriculture*, 5th Edition. Indian Council of Agriculture Research, New Delhi.

Imbellone, P.A., Guichon, B.A. and Gimenez, J.E. (2001). Dynamics of physical-chemical properties in soils with anthropic flooding, Buenos Aires Province, Argentina. *Soil Sci* 166:930–939.

Jain, N., Dubey, R., Dubey, D.S., Singh, J., Khanna, M., Pathak, H. and Bhatia, A. (2013). Mitigation of greenhouse gas emission with system of rice intensification in the Indo-Gangetic Plains. *Paddy Water Environ* DOI 10.1007/s10333-013-0390-2.

Kabir, H. and Uphoff, N. (2007). Results of disseminating the system of rice intensification with farmer field school methods in Northern Myanmar. *Exp/ Agril* 43:463-476.

Kar, S., Varade, S.B., Subramanyam, T.K. and Ghildyal, B.P. (1974). Nature and growth pattern of rice root system under submerged and unsaturated conditions. *Il Riso* 23:173–179.

Kassam, A., Stoop, W. and Uphoff, N. (2011). Review of SRI modifications in rice crop and water management and research issues for making further improvements in agricultural and water productivity. *Paddy Water Environ* 9: 163-180.

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

Kirk, G.J.D. (2001). Plant-mediated processes to acquire nutrients: nitrogen uptake by rice plants. *Plant Soil* 232: 129-134.

Krouk, G., Lacombe, B., Bielach, A., Perrine-Walker, F., Malinska, K., Mounier, E., Hoyerova, K., Tillard, P., Leon, S., Ljung, K., Zazimalova, E., Benkova, E., Nacry, P. & Gojon, A. (2010). Nitrate-regulated auxin transport by NRT1.1 defines a mechanism for nutrient sensing in plants. *Developmental Cell* 18: 927-937.

Laulanié, H. (1993). Le système de riziculture intensive malgache. *Tropicultura* 11:110–114.

Ly, P., Jensen, L. S., Bruun, T. B., Rutz, D. and de Neergaard, A. (2012). The system of rice intensification: adapted practices, reported outcomes and their relevance in Cambodia. *Agricultural Systems* 113: 16-27.

Mahajan, G., Gill, M.S. and Singh, K. (2010). Optimizing seed rate to suppress weeds and to increase yield in aerobic direct-seeded rice in northwestern Indo-Gangetic plains. *J New Seeds* 11:225-238.

McDonald, A.J., Hobbs, P.R. and Riha, S.J. (2006). Does the system of rice intensification outperform conventional best management? A synopsis of the empirical record. *Field Crops Res.,* 96: 31–36.

Menete, M.Z.L., van Es, H.M., Brito, R.M.L., DeGloria, S.D. and Famba, S. (2008). Evaluation of system of rice intensification (SRI) component practices and their synergies on salt-affected soils. *Field Crops Res* 109:34-44.

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

Mishra, A., Whitten, M., Ketelaar, J.W. and Salokhe, V.M. (2006). The system of rice intensification (SRI): a challenge for science, and an opportunity for farmer empowerment towards sustainable agriculture. *Int J Agr Sust* 4:193-212.

Muirhead, W.A., Blackwell, J.B., Humphreys, E., and White, R.J.G. (1989). The growth and nitrogen economy of rice under sprinkler and flood irrigation in south-east Australia. I. Crop response and N uptake. *Irrig. Sci.* 10:183-199.

Namara, R., Bossio, D., Weligamage, P. and Herath, I. (2008). The practice and effects of the System of Rice Intensification (SRI) in Sri Lanka. *Quarterly J Int Agr* 47(1):5-23.

Namara, R.E., Weligamage, P. and Barker R. (2004). Prospects for adopting system of rice intensification in Sri Lanka: A socioeconomic assessment. International Water Management Institute Research Report 75.

Ndiiri, J.A., Mati, B.M., Home, P.G., Odongo, B. and Uphoff, N. (2013). Adoption, constraints and economic returns of paddy rice under thesystem of rice intensification in Mwea, Kenya. *Agricultural Water Management* 129: 44-55.

Nemoto, K., Morita, S. and Baba, T. (1995). Shoot and root development in rice related to the phyllochron. *Crop Sci* 35:24-29.

Nguyen, H.T., Fischer, K.S. and Fukai, S. (2009). Physiological responses to various water saving systems in rice. *Field Crops Res* 112:189-198.

Nie L, Peng S, Chen M, Shah F, Huang J, Cui K, and Xiang J. (2012). Aerobic rice for water-saving agriculture: A review. *Agron. Sustain. Dev.* 32:411-418.

Normile, D. (2006). Consortium aims to supercharge rice photosynthesis. Science 313 (5786): 423.

Olaleye, A.O., Tabi, F.O., Ogunkunle, A.O., Singh, B.N. and Sahrawat, K.L. (2001). Effect of toxic iron concentrations on the growth of lowland rice. *J Plant Nutr* 24:441–457.

Ookawa, T., Naruoka, Y., Sayama, A. and Hirasawa, T. (2004). Cytokinin effects on ribulose-1, 5-bisphosphate carboxylase/oxygenase and nitrogen partitioning in rice during ripening. *Crop Sci* 44:2107–2115.

Pasuquin, E., Lafarge, T. and Tubana, B. (2008). Transplanting young seedlings in irrigated rice fields: Early and high tiller production enhanced grain yield. *Field Crops Res* 105:141–155.

Rao, A.N., Johnson, D.E., Sivaprasad, B., Ladha, J.K. and Mortimer, A.M. (2007). Weed management in direct-seeded rice. *Adv Agron* 93:153-255.

Rejesus, R.M., Palis, F.G., Rodriguez, D. G.P., Lampayan, R.M. and Bouman, B.A.M. (2011). Impact of the alternate wetting and drying (AWD) water-saving irrigation technique: Evidence from rice producers in the Philippines. *Food Policy* 36: 280-288.

Sahrawat, K.L. (2000). Elemental composition of the rice plant as affected by iron toxicity under field conditions. *Commun Soil Sci Plant Anal* 132:2819–2827.

Samejima, H., Kondo, M., Ito, O., Nozoe, T., Shinano, T. and Osaki, M. (2004). Root-shoot interaction as a limiting factor of biomass productivity in new tropical rice lines. *Soil Sci Plant Nutr* 50:545-554.

San-oh, Y., Mano, Y., Ookawa, T. and Hirasawa, T. (2004). Comparison of dry matter production and associated characteristics between direct-sown and transplanted rice plants in a submerged paddy field and relationships to planting patterns. *Field Crops Res* 87:43-58.

San-oh, Y., Sugiyama, T., Yoshita, D., Ookawa, T. and Hirasawa, T. (2006). The effect of planting pattern on the rate of photosynthesis and related processes during ripening in rice plants. *Field Crops Res* 96:113-124.

Sato, S. and Uphoff, N. (2007). A review of on-farm evaluation of system of rice intensification (SRI) methods in eastern Indonesia. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources, 2, 54. Commonwealth Agricultural Bureau International, Wallingford, UK.

Sato, S., Yamaji, E. and Kuroda, T. (2011). Strategies and engineering adaptions to disseminate SRI methods in large-scale irrigation systems in Eastern Indonesia. *Paddy and Water Environment* 9:79-88.

Satyanarayana, A., Thiyagarajan, T.M. and Uphoff, N. (2007). Opportunities for water saving with higher yield from the system of rice intensification. *Irrigation Sci* 25:99-115.

Senthilkumar, K., Bindraban, P.S., Thiyagarajan, T.M., de Ridder, N. and Giller, K.E. (2008). Modified rice cultivation in Tamil Nadu, India: Yield gains and farmers' (lack of) acceptance. *Agric Syst* 98:82-94.

Sheehy, J.E., Mitchell, P.L. and Hardy, B. (2007). Charting new pathways to C4 rice. Los Baños (Philippines): International Rice Research Institute. 422p.

Sheehy, J.E., Peng, S., Dobermann, A., Mitchell, P.L., Ferrer, A., Yang, J., Zou, Y., Zhong, X. and Huang, J. (2004). Fantastic yields in the system of rice intensification: fact or fallacy? *Field Crops Res.* 88:1–8.

Shi, Q., Zeng, X., Li, M., Tan, X. and Xu, F. (2002). Effect of different water management practice on rice growth. In: Bouman, B.A.M. et al. (Eds.), Water-Wise Rice Production. IRRI, Los Baños, Philippines, pp. 3–13.

Singh, S., Ladha, J.K., Gupta, R.K., Bhushan, L. and Rao, A.N. (2008). Weed management in aerobic rice systems under varying establishment methods. *Crop Prot* 27:660–671.

Sinha, S.K. and Talati, J. (2007). Productivity impacts of the system of rice intensification (SRI): A Case Study in West Bengal, India. *Agric Water Manage* 87:55-60.

Soejima, H., Sugiyama, T. and Ishihara, K. (1995). Changes in the chlorophyll contents of leaves and in levels of cytokinins in root exudates during ripening of rice cultivars *Nipponbare and Akenohoshi. Plant Cell Physiol* 36:1105-1114.

Stoop, W.A. and Kassam, A.H. (2005). The SRI controversy: A response. *Field Crops Res.,* 91: 357–360.

Stoop, W.A., Adam, A. and Kassam, A. (2009). Comparing rice production systems: A challenge for agronomic research and for the dissemination of knowledge-intensive farming practices. *Agric Water Manage* 96:1491-1501.

Stoop, W.A., Uphoff, N. and Kassam, A. (2002). A review of agricultural research issue raised by the System of Rice Intensification (SRI) from Madagascar: Opportunities for improving system for resource poor farmers. *Agric Syst* 71:249-274.

Styger, E., Ag Attaher, M., Guindo, H., Ibrahim, H., Diaty, M., Abba, I. and Traore, M. (2011). Application of system of rice intensification practices in the arid environment of the Timbuktu region in Mali. *Paddy and Water Environment* 9: 137-144.

Suryavanshi, P., Singh, Y.V., Prasanna, R., Bhatia, A. and Shivay, Y.S. (2013). Pattern of methane emission and water productivity under different methods of rice crop establishment. *Paddy Water Environ* 11: 321–329.

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

Takahashi, K. (2013). The roles of risk and ambiguity in the adoption of the system of rice intensification (SRI): evidence from Indonesia. *Food Sec.* 5:513–524.

Thakur, A.K., Mohanty, R.K., Patil, D.U. and Kumar, A. (2014). Impact of water management on yield and water productivity with system of rice intensification (SRI) and conventional transplanting system in rice. *Paddy Water Environment* 12:413-424.

Thakur, A.K., Rath, S. and Mandal, K.G. (2013). Differential responses of system of rice intensification (SRI) and conventional flooded rice management methods to applications of nitrogen fertilizer. *Plant Soil* 370: 59–71.

Thakur, A.K., Rath, S., Patil, D.U. and Kumar, A. (2011). Effects on rice plant morphology and physiology of water and associated management practices of the system of rice intensification and their implications for crop performance. *Paddy Water Environ* 9: 13-24.

Thakur, A.K., Rath, S., Roychowdhury, S. and Uphoff, N. (2010a). Comparative performance of rice with system of rice intensification (SRI) and conventional management using different plant spacings. *Journal of Agronomy & Crop Science* 196:146-159.

Thakur, A.K., Uphoff, N. and Antony, E. (2010b). An assessment of physiological effects of system of rice intensification (SRI) practices compared with recommended rice cultivation practices in India. *Expl Agric* 46: 77-98.

Thiyagarajan, T.M. and Gujja, B. (2012). Transforming rice production with SRI knowledge and Practice: Reducing Agriculture Foot Print and Ensuring Food Security. Published by NCS, India

Toriyama, K. and Ando, H. (2011). Towards an understanding of the high productivity of rice with system of rice intensification (SRI) management from the perspectives of soil and plant physiological processes. *Soil Sci Plant Nutr* 57: 636–649.

Tsujimoto, Y., Horie, T., Randriamihary, H., Shiraiwa, T. and Homma, K. (2009). Soil management: The key factors for higher productivity in the fields utilizing the system of rice intensification (SRI) in the central highland of Madagascar. *Agric Syst* 100:61–71.

Tuong, T.P., Bouman, B.A.M. and Mortimer, M. (2005). More rice, less water—integrated approaches for increasing water productivity in irrigated rice-based systems in Asia. *Plant Prod Sci* 8:231-241.

Tuong, T.P. and Bouman, B.A.M. (2002). Rice production in water-scarce environments. Paper Presented at the Water Productivity Workshop, 12–14 November 2001. Colombo, Sri Lanka.

Tuong, T.P., Bouman, B.A.M., and Mortimer, M. (2004). More rice, less water-Integrated approaches for increasing water productivity in irrigated rice-based systems in Asia. ‘‘New Directions for a Diverse Planet.’’ Proceedings of the 4th International Crop Science Congress, 26 September–1 October 2004. Brisbane Australia (published on CDROM).

Uphoff, N. (2003). Higher yields with fewer external inputs? The system of rice intensification and potential contributions to agricultural sustainability. *Int J Agr Sust* 1:38-50.

Uphoff, N. (2007). The System of Rice Intensification: Using alternative cultural practices to increase rice production and profitability from existing yield potentials. International Rice Commission Newsletter, No. 55. Food and Agriculture Organization, Rome

Uphoff, N., Fernandes, E.C.M., Longping, Y., Jiming, P., Rafalahy, S., Rabenandrasana, J. eds. (2002). Assessments of the System of Rice Intensification: Proceedings of an International Conference, Sanya, China, April 1–4, 2002. 200pp.

Uphoff, N., Kassam, A. and Stoop, W. (2008). A critical assessment of a desk study comparing crop production systems: The example of the 'system of rice intensification' versus 'best management practice'. *Field Crops Res.* 108: 109–114.

Yang, J., Liu, K., Wang, Z., Du, Y. and Zhang, J. (2007). Water saving and high-yielding irrigation for lowland rice by controlling limiting values of soil water potential. *J Integr Plant Biol* 49:1445-1454.

Yang, C., Yang, L., Yang, Y. and Ouyang, Z. (2004). Rice root growth and nutrient uptake as influenced by organic manure in continuously and alternately flooded paddy soils. *Agric Water Manage* 70:67–81.

Yang, J., Zhang, J., Huang, H., Wang, Z., Zhu, Z. and Liu, L. (2002). Correlations of cytokinin levels in the endosperms and roots with cell number and cell division activity during endosperm development in rice. *Ann Bot* (Lond) 90:369–377.

Zhang, H., Zhang, S., Zhang, J., Yang, J. and Wang, Z. (2008). Post-anthesis moderate wetting drying improves both quality and quantity of rice yield. *Agron J* 100:726-734.

Zhang, H., Xue, Y., Wang, Z., Yang, J. and Zhang, J. (2009a). An alternate wetting and moderate soil drying regime improves root and shoot growth in rice. *Crop Sci* 49: 2246-2260.

Zhang, H., Xue, Y., Wang, Z., Yang, J. and Zhang, J. (2009b). Morphological and physiological traits of roots and their relationships with shoot growth in ''super'' rice. *Field Crops Res* 113:31-40.

Zhao, L.M., Wu, L.H., Li, Y.S., Animesh, S., Zhu, D,F. and Uphoff, N. (2010). Comparisons of yield, water use efficiency, and soil microbial biomass as affected by the system of rice intensification. *Commun Soil Sci Plant Anal* 41: 1-12.

Zhao, L.M., Wu, L.H., Li, Y.S., Lu, X.H., Zhu, D.F. and Uphoff, N. (2009). Influence of the system of rice intensification on rice yield and nitrogen and water use efficiency with different N application rates. *Expl Agric* 45: 275-286.

Zhao, X.Q., Zhao, S.P. and Shi, W.M. (2008). Enhancement of NH4+uptake by NH3- in relation to expression of nitrate induced genes in rice *(Oryza sativa)* roots. *Pedosphere* 18: 86–91.

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