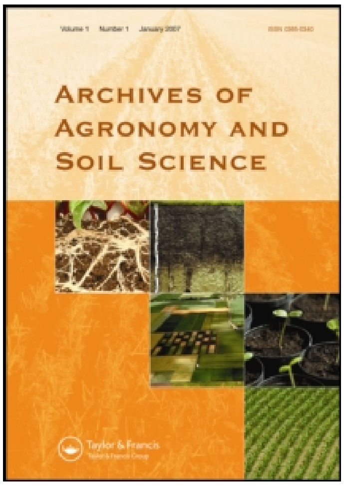

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Performance evaluation of rice varieties under the System of Rice Intensification compared with the conventional transplanting system

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Performance evaluation of rice varieties under the System of Rice Intensification compared with the conventional transplanting system

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A field experiment was conducted at Deras Research Farm, Khurda district, Bhubaneswar, Orissa, India, to evaluate the performance of different rice varieties managed under System of Rice Intensification (SRI) compared with the current transplanting system (CTS). Five rice varieties were used for the study: (i) Khandagiri (early-duration, 90 days); (ii) Lalat (early-medium duration, 110 days); (iii) Surendra (late-medium duration, 130 days); (iv) Hybrid CRHR-7 (late-medium duration, 135 days); and (v) Savitri (long-duration, 145 days). It was seen that SRI practices significantly ($p < 0.05$) improved the harvest index, percentage of effective tillers, panicle length, and various yield components in all the varieties. SRI hills having an open-canopy structure with higher leaf area index (LAI) resulted in greater light interception than the conventional transplanting methods. At the ripening stage, SRI plants had better root growth and a higher xylem exudation rate than CTS plants. This was associated with higher levels of chlorophyll in the lower leaves and a higher photosynthesis rate. Delayed senescence with enhanced photosynthesis in the lower leaves was also responsible for supplying more assimilates toward the roots for maintaining their higher activity. These features might also contribute to the improvement of grain filling and grain weight in SRI-grown plants as all the varieties performed better in terms of grain yield (12–42% higher) with this alternative management.

Keywords: SRI; cultivation method; photosynthesis rate; light interception; grain yield

Introduction

Rice currently feeds more than half the world's population, and demand for rice is expected to rise by almost 40% within 30 years due to population increase (Surridge 2004). The per capita availability of paddy in Asia has decreased from 154 kg in 1989 to 139 kg in 2003; similarly in India it has fallen from 133–122 kg during the same period (Source: FAOSTAT). At the same time many rice-producing countries are facing water scarcity for their agricultural production (Seckler et al. 1999), so water-saving strategies have become a priority in rice research (Baker et al. 2000).

The System of Rice Intensification (SRI), which was developed in Madagascar, has brought hope to many rice farmers as it claims to accomplish more rice per drop of water (WWF-ICRISAT 2007). It is a methodology for comprehensively managing

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resources, i.e. changing the way that land, seeds, water, nutrients and human labour are utilized (Uphoff 2003). SRI is an amalgamation of multiple beneficial practices, being a low-cost, high-yielding system that could be a sustainable alternative to conventional paddy production (Batuwitage 2002). Many reports showed yield-enhancement by 25–50% or more on the basis of field experiences or on-farm trials (Uphoff 2002; Ceesay et al. 2006; Kabir and Uphoff 2007; Satyanarayana et al. 2007; Sinha and Talati 2007; Zhao et al. 2009).

At the same time, some experts have argued that SRI does not really lead to higher yields and that the reported high yields with SRI management are a measurement error and deserve no attention (Sheehy et al. 2004; Sinclair 2004). The criticism is made that SRI is not backed up by solid agronomic research data (Dobermann 2004). Both proponents and opponents have expressed the need for critical experiments to evaluate and explain the yield benefits and other aspects of SRI (Sinclair 2004; Uphoff 2004; Satyanarayana et al. 2007).

Generally, long-duration varieties perform better with wider spacing than short-duration varieties (Baloch et al. 2002). Stoop (2005) suggested that long-duration varieties may perform better under SRI management practice because of extended crop growth cycle. Latif et al. (2005) also reported that long-duration varieties like BRRI's Dhan29 are most suitable for SRI practices, as it gave highest yield. However, a very limited study was carried out by Latif et al. (2005) and there are no studies of the comparative performance of different-duration varieties under SRI and conventional system, with attention to their physiological basis.

The objective of the present study was to investigate whether variation in vegetative-growth period had any role in yield improvement, and how different-duration rice varieties might perform under System of Rice Intensification (SRI) management compared with the current transplanting system (CTS) in terms of yield and yield-contributing attributes, root growth and activity, canopy structure, and light interception and utilization. These parameters, if properly measured and compared, can help to resolve some of the controversy surrounding SRI in the agronomic literature and could also contribute to improvements in rice culture.

Materials and methods

An experiment was conducted at Deras Research Farm, Mendhasal, Khurda district of Orissa, India (20°30′ N, 87°48′10″ E) during the wet season (July–December), 2006 and 2007. Soil of the experimental site is sandy clay-loam in texture (63% sand, 16% silt, and 21% clay) having pH of 5.5 and classified as *Aeric Haplaquepts*. Five rice varieties: (i) Khandagiri (early-duration, 90 days); (ii) Lalat (early-medium duration, 110 days); (iii) Surendra (late-medium duration, 130 days); (iv) Hybrid CRHR-7 (late-medium duration, 135 days), and (v) Savitri (long-duration, 145 days), were grown by the SRI method and compared with crops grown under the current transplanting system (CTS).

This experiment was conducted using a split-plot design with three replications and subplot sizes of 10 × 5 m. In the main plots, rice was grown under the two alternative crop management systems being assessed: (i) The System of Rice Intensification (SRI), and (ii) the CTS, with the different varieties grown in subplots. All plots were surrounded by 50-cm wide bunds to prevent lateral seepage between plots, followed by 50-cm wide channels for irrigation and drainage.

For the SRI trials, 14-day-old single seedlings of all the varieties were planted with spacing of 20 × 20 cm, a closer spacing than recommended (Stoop et al. 2002) because in another experiment we found highest grain yield at this spacing for SRI (Thakur et al. 2009). In CTS trials, 25-day-old seedlings, three per hill, were planted with spacing of 15 × 10 cm for Khandagiri, 20 × 10 cm for Lalat and Surendra, 20 × 20 cm for CRHR-7, and 20 × 15 cm for Savitri. Soils in all the plots under SRI management were kept moist, without any ponded water, throughout the vegetative phase. In CTS plots, on the other hand, standing water was maintained at 3–5 cm depth during the vegetative stage. After panicle initiation, all plots were kept flooded with a thin layer of water 1–2 cm, and all were drained 15 days before harvest. SRI plots were weeded by cono-weeder at 10, 20 and 30 days after transplanting (DAT); CTS plots had three hand-weedings at the same intervals. This meant that the SRI weeding introduced soil aeration as a variable while CTS treatments had only weed removal.

Soil fertilization was not introduced as a variable in this evaluation. With both cultivation practices, organic manure (mixed with cow dung and straw) was applied at the rate of 5 t ha^{-1} along with chemical fertilizer: urea, single super phosphate (SSP), and muriate of potash (MOP) at the respective rates of 60 kg N ha^{-1}, 30 kg P_2O_5 ha^{-1}, 30 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, and 25% at panicle initiation stage. While the SRI recommendation is for organic fertilization in preference to chemical fertilization, in this study we did not make this practice an additional factor to be assessed.

Root dry weight and xylem exudation rate

Three hills from each replicate were randomly selected at the early-ripening stage, and root samples were collected by removing uniform volume of soil (15 cm deep) along with the hill using an auger of 10 cm diameter (Kawata and Katano 1976). Roots were carefully washed, and dry weight were measured (Yoshida 1981).

Xylem exudation rate was measured at the early-ripening stage. From each replicate, three hills were selected, each with an average number of panicles: 11 ± 1, 13 ± 1, 13 ± 1, 14 ± 1, and 16 ± 1 in the SRI plots; and 3 ± 1, 6 ± 1, 6 ± 1, 13 ± 1, and 11 ± 1 panicles in the CTS plots, representing Khandagiri, Lalat, Surendra, CRHR-7 and Savitri variety, respectively. Stems were cut at 10 cm from the soil surface, and pre-weighed cotton wool packed in a polythene bag was attached to the cut end of each stem with tape. After 24 h, each bag was detached, sealed and weighed. 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).

Measurements of leaf area, light interception by the canopy, and inclinations of stems

To assess leaf area, three hills were randomly selected from each replicate, and the leaf area of one m^2 was measured during the flowering stage using a leaf area meter (LICOR-3100 Area Meter). 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 to 12:00 h at flowering stage. The light intensity at the surface of the soil relative to the intensity above the canopy was measured at consecutive points at intervals of 1 m apart in the inter-row space and in the inter-hill space, respectively (San-oh et al. 2004). Light interception by the canopy (LIC) was calculated, as a percentage, from the following equation:

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

Three hills with average number of panicles were selected from each replicate at the early ripening stage for measurements of inclinations of stems. The angle of inclination from horizontal was measured for each stem at the centre of the neck node of a panicle with a protractor (San-oh et al. 2004).

Measurements of photosynthesis rate and chlorophyll content

The fourth leaf from the top at early-ripening stage was marked to measure photosynthesis rate with the use of a CIRAS-2 Portable Photosynthesis System (PP Systems, UK). These measurements were taken on a clear sunny day (solar radiation $>1200\ \mu$mol m^{-2} s^{-1}) between 10:30 and 11:00 h before midday reduction in photosynthesis.

Chlorophyll content was determined in the same fourth leaf at early-ripening stage. 200 mg of fresh leaf tissue was taken and cut into small pieces, and chlorophyll pigments were extracted using 10 ml dimethyl sulfoxide (DMSO) solution at 65°C for 3 h (Hiscox and Israelstam 1979), filtered through Whatman No. 1 filter paper. Absorption of the chlorophyll extract was measured using a UV-Vis Spectrophotometer (Model: Chemito, 2600) at wavelengths of 645 and 663 nm, using DMSO as the blank. Chlorophyll content of leaves were calculated as suggested by Hipkins and Baker (1986) and expressed as mg g^{-1} fresh leaf weight.

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 2 $\times$ 2 m for each replicate were harvested (excluding the border rows) for determination of yield per unit area, and 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 replication. 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 replication. The percentage of ripened grains was calculated by dividing the number of filled grains by the number of total grains.

Statistical analysis

The data sets collected during both years of experimentation for the various parameters were statistically analyzed using Bartlett's test for homogeneity of variance by following split-split plot design, considering year as a source of variation. During factorial analysis, first factor (year) was assigned to the main plot, the second factor (practice) to the subplot, and the third factor (variety) to the sub-subplot. This test showed that the main effects of year and interaction effect between year and practice (year × practice), year and variety (year × variety) and three-factor interaction (year × practice × variety) were non-significant for all the parameters considered in the study. Consequently, means were compared by LSD-tests between the practice, variety and their interaction at the 5% level of significance (Gomez and Gomez 1984).

Results and discussion

Yield and yield-contributing characteristics

All the rice varieties of different duration tried in the experiment had significantly higher yields (by an average of 28%) under SRI practice ($p < 0.05$) compared to the conventional transplanting method (Table 1). Among the varieties, in absolute terms, CRHR-7 and Savitri gave the highest grain yield, under SRI management, while Khandagiri produced the least grain. However, in terms of relative increase, Khandagiri, a short-duration variety, produced 33% higher grain under SRI compared to CTS. Similarly, the medium-duration rice varieties Lalat and Surendra gave 36 and 42% more grain with SRI management than when grown under CTS, respectively. Varieties with long duration, CRHR-7 (hybrid) and Savitri, under SRI management gave only 12 and 22% more grain yield compared to CTS.

Conventional transplanting method produced significantly higher straw weight than SRI. On the other hand, Savitri, a long-duration variety, produced the highest straw amount, followed by Khandagiri. With SRI methods, the straw weight was significantly higher for the long-duration variety compared to short- and medium-duration varieties. The harvest index was significantly larger for SRI (20.5% higher) compared to CTS for all varieties. Therefore, differences in the grain yield were due in large part to differences in the harvest index.

Various yield-contributing characteristics like panicle length, grain number per panicle, 1000-grain weight, and percent of grain filling were significantly enhanced under SRI management in all the varieties. There was a 10% increase in panicle length in SRI plants compared to the CTS crop (Table 2). Savitri had the longest panicles, and Khandagiri had the shortest panicles. The longer panicles in SRI also accommodated more number of grains per panicle, and the number of grains/panicle increased by 33% in the different varieties grown under SRI compared to CTS. 1000-grain weight and grain-filling percent were also significantly higher in SRI than CTS in all the varieties (Table 2).

In the present study, it is seen that all the varieties yielded more under SRI, with improvement in harvest index and significant enhancement in yield-components. This confirms earlier reports on SRI that showed grain yield increase (Ceesay et al. 2006; Satyanarayana et al. 2007; Sinha and Talati 2007; Kabir and Uphoff 2007; Sato and Uphoff 2007; Zhao et al. 2009). The increase in yield in SRI practice compared to CTS was more for medium-duration varieties (Lalat and Surendra) than short-duration variety (Khandagiri). However, this difference was less for long-duration variety (Savitri) and least for hybrid (CRHR-7). The long-duration variety might have faced some constraints of space due to the protocol used so that its full potential may not have been exploited with SRI practices. Another study has shown that optimum spacing for getting maximum yield under SRI for long-duration variety was 25 × 25 cm (Thakur et al. 2009). In the case of the hybrid variety, where

Table 1. Comparison of grain yield, straw weight, and Harvest Index of different rice varieties grown under SRI and current transplanting system (CTS).

Variety	Duration (days)	Grain yield[a] ($t\ ha^{-1}$)			Straw weight ($g\ m^{-2}$)			Harvest Index[b]		
		SRI	CTS	Mean	SRI	CTS	Mean	SRI	CTS	Mean
Khandagiri	90	4.25	3.18	3.72	524.4	904.2	714.4	0.45	0.26	0.35
Lalat	110	5.68	4.16	4.92	609.8	616.7	613.2	0.48	0.40	0.44
Surendra	130	6.25	4.39	5.32	647.9	617.2	632.6	0.49	0.42	0.45
CRHR-7	135	6.06	5.37	5.72	659.6	623.0	641.3	0.48	0.46	0.47
Savitri	145	6.26	5.12	5.69	733.8	773.8	753.8	0.46	0.40	0.43
Mean (SRI change)		5.70	4.45	(28.1%)	653.1	707.0	(−7.6%)	0.47	0.39	(20.5%)
$LSD_{0.05}$										
Practice (P)			0.17			6.7			0.01	
Variety (V)			0.16			17.9			0.01	
P × V			0.23			25.3			0.01	

[a]Grain yield was measured from crop harvested from 4 m^2 area from each replicate; [b]Harvest Index was calculated by dividing the grain yield weight by the dry weight of aboveground parts.

Table 2. Comparison of panicle length and yield components of different rice varieties grown under SRI and current transplanting system (CTS).

Variety	Panicle length[a] (cm)			Grain number/panicle[a]			Grain filling[b] (%)			1000-grain weight[c] (g)		
	SRI	CTS	Mean	SRI	CTS	Mean	SRI	CTS	Mean	SRI	CTS	Mean
Khandagiri	19.24	18.67	18.95	129.7	94.2	111.94	81.6	73.2	77.4	24.48	23.96	24.22
Lalat	20.32	18.93	19.63	155.8	114.1	134.93	84.6	76.0	80.3	24.79	24.12	24.45
Surendra	22.45	19.43	20.94	164.3	131.5	147.92	86.1	77.1	81.6	24.99	24.39	24.69
CRHR-7	21.33	19.61	20.47	163.0	113.8	138.43	84.0	81.3	82.6	25.04	24.55	24.79
Savitri	22.47	19.58	21.02	170.9	136.3	153.59	86.1	83.1	84.6	25.07	24.81	24.94
Mean (SRI change)	21.16	19.24	(10.0%)	156.7	117.98	(32.8%)	84.4	78.1	(8.1%)	24.87	24.36	(2.1%)
$LSD_{0.05}$												
Practice (P)		0.67			4.23			1.6			0.17	
Variety (V)		0.58			7.22			2.3			0.15	
P × V		0.82			10.20			3.3			0.21	

[a]Panicle length and grains per panicle was measured from one square meter area from each replicate; [b]Grain filling percentage was calculated by dividing the number of filled grains by the number of total grains; [c]The 1000-grain weight was calculated for a seed moisture content of 14.5%.

the numbers of hills were similar under both practices (25 m^{-2}), the 12% increase in grain yield under SRI management is certainly the effect of SRI practices apart from spacing.

Number of tillers and panicles

The number of tillers per hill in SRI was approximately 1.5 times higher than with CTS, and this varied, respectively, from 12–16 and 5–15 in SRI and conventional transplanted crop (Table 3). Similarly, number of panicles per hill was also significantly higher in all the varieties grown under SRI than with the CTS method. Savitri and CRHR-7 had significantly higher number of tillers and panicles per hill than the others. In spite of more number of tillers in each hill, tillers in unit area is significantly lower in SRI crop than with CTS. Still the number of panicles/m^2 was significantly higher in SRI compared to CTS.

Among the varieties, lowest number of tillers or panicles per m^2 was in Khandagiri and highest in Savitri. The percentage of effective tillers was significantly enhanced (by 15%) in SRI compared to CTS in all the varieties. The highest percentages of effective tillers were found in hybrid variety, CRHR-7, followed by long-duration variety, Savitri, and it was least in short-duration variety, Khandagiri.

The significant increase in number of tillers under SRI may be because individual plants reached the 10th or 11th phyllochron (a time period required for the development of one or a set of phytomers) and accordingly produced a higher number of tillers (Nemoto et al. 1995). However, a rice plant raised under the current transplanted method, with older seedlings planted more densely, reaches only up the 7th or 8th phyllochron of growth before anthesis and produces lesser numbers of tillers per hill (Stoop et al. 2002). Planting of younger seedlings with optimal growing conditions is responsible for accelerated growth rate with SRI plants as these are able to complete more phyllochrons before entering into their reproductive phase (Nemoto et al. 1995; Berkelaar 2001). Longer–duration varieties have a longer vegetative period and thus get more time to produce tillers than do short- or medium-duration varieties. This leads to both higher tiller numbers/hill and enhanced production of effective tillers. Improvement in the percentage of effective tillers with SRI management is one of the important changes responsible for making SRI a more productive cultural system.

Angle of inclinations of stem, leaf area index, and light interception

Under SRI management, new tillers emerged from the culm with at an angle less inclination of tillers or stems from the horizontal than with CTS. The spread of tillers was greater in all the varieties grown under SRI than under CTS (Table 4). Tillers in CTS hills had a higher angle of inclination from horizontal, and their spread was lower. Significantly, a higher leaf area index (LAI) at the flowering stage was recorded in all the varieties grown under SRI compared to CTS (Figure 1). Light interception was also significantly higher in SRI plots than in CTS plots for all the varieties (Figure 1). Among the varieties under SRI, the highest LAI and light interception was in the long-duration variety, Savitri, and these parameters were lowest in short-duration variety.

Emergence of new tillers in SRI hills with a more divergent angle in comparison to hills of conventionally-transplanted rice might be due to shallower planting of

Table 3. Comparison of tiller, panicle numbers and percent effective tillers of different rice varieties under SRI and CTS.

	Ave. tiller number ($hill^{-1}$)			Tiller number (m^{-2})			Ave. panicle number ($hill^{-1}$)			Panicle number (m^{-2})			Effective tillers[a] (%)		
Variety	SRI	CTS	Mean	SRI	CTS	Mean	SRI	CTS	Mean	SRI	CTS	Mean	SRI	CTS	Mean
Khandagiri	12.1	5.2	8.7	302.8	344.7	323.8	11.4	3.8	7.6	284.6	248.6	266.6	94.0	72.1	83.1
Lalat	13.9	7.3	10.7	349.0	382.2	365.6	13.5	6.3	9.9	336.7	312.5	324.6	96.5	81.8	89.2
Surendra	13.9	7.5	10.7	348.8	374.8	361.8	13.6	6.3	9.9	338.8	315.0	326.9	97.1	84.1	90.6
CRHR-7	14.1	15.1	14.6	353.5	378.5	366.0	13.6	14.0	13.8	340.8	349.6	345.2	96.4	92.4	94.4
Savitri	16.1	12.7	14.4	402.5	419.8	411.2	15.7	11.2	13.4	391.3	369.1	380.2	97.2	87.9	92.6
Mean (SRI change)	14.1	9.6	(46.9%)	351.3	380.0	(−7.6%)	13.5	8.3	(62.7%)	338.4	319.0	(6.1%)	96.25	83.7	(15.0%)
$LSD_{0.05}$															
Practice (P)		0.6			16.9			0.3			3.6			4.1	
Variety (V)		0.6			16.5			0.7			19.5			3.4	
P × V		0.8			ns			0.9			27.6			4.9	

[a]Effective tillers was calculated by dividing the panicle number by tiller number per m^2; ns, non-significant.

Table 4. Comparison of angles of inclination of stems (in degree) from horizontal in the canopy of different varieties under SRI and CTS at the early ripening stage.

Variety	Angle of inclination of stem (°)		
	SRI	CTS	Mean
Khandagiri	69.7	80.7	75.2
Lalat	69.5	81.3	75.4
Surendra	69.4	79.2	74.3
CRHR-7	67.8	79.0	73.4
Savitri	66.4	77.5	72.0
Mean (SRI change)	68.6	79.6	(−13.8%)
$LSD_{0.05}$			
Practice (P)		2.6	
Variety (V)		2.5	
P × V		ns	

ns, non-significant.

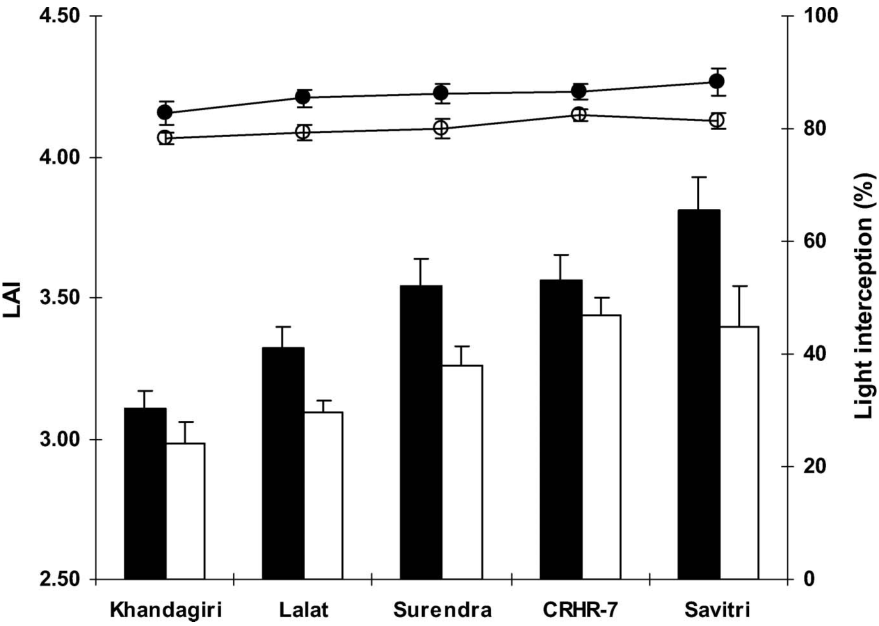

Figure 1. Leaf area index (LAI) and light interception by canopy at flowering stage. Black and white bars represent LAI in SRI and CTS plots, respectively. Closed and open circles represent light interception in SRI and CTS plots, respectively. Vertical bars represent the standard deviation ($n = 6$).

young seedlings in SRI practice. Newly-emerged tillers from three deeply-inserted seedlings in CTS also experience competition for space, and this results in a more compact structure of hills with closely bound tillers. Greater stems spread outward in the case of SRI, also a result of the larger number of tillers in each hill. Open plant structure in SRI gave more coverage to the ground area and was able to intercept more light. Especially the lowermost leaves could also get sufficient light.

These features help to support the effective functioning of lower leaves, which supply most of the assimilates towards rice root systems and thereby helps in maintaining root activity, especially during later phases of growth. The interception of solar radiation at the flowering (anthesis) stage by the canopy of SRI plants was greater mainly due to their open-canopy structure, higher leaf area index (LAI), and greater leaf size (data not shown). The dry matter production of the canopy depends on its absorption of solar radiation, which is significantly affected by the LAI (Gardner et al. 1985; San-oh et al. 2004, 2006). Similarly, in the present study, higher LAI with greater spread of canopy was responsible for enhanced light interception and greater dry matter production in SRI compared to the conventional transplanted system.

Chlorophyll content and rate of photosynthesis

Chlorophyll content of fourth leaves from the flag leaf was found to be significantly higher in SRI plants (by 27–73%) compared to CTS plants in all the varieties during early ripening or milk grain stage (Figure 2). Leaves of Khandagiri variety had the lowest chlorophyll content grown under both SRI and conventional method. Interestingly, the difference in chlorophyll content between leaves of SRI and CTS was greatest in the short-duration variety (Khandagiri), and these differences were lower in the long-duration and hybrid varieties.

Similarly, the rate of photosynthesis was also higher for the fourth leaves from the flag leaf at the early ripening stage of SRI plants compared to CTS (Figure 3). Leaves from SRI plants showed photosynthesis rates 48–69% higher than in CTS leaves. The hybrid and long-duration variety maintained significantly higher rates of photosynthesis than did the short-duration variety under both SRI and CTS.

A close relationship between levels of chlorophyll and the rate of photosynthesis at the ripening stage is well established (Makino et al. 1984). When comparing the chlorophyll content and rate of photosynthesis with senescence, SRI plants

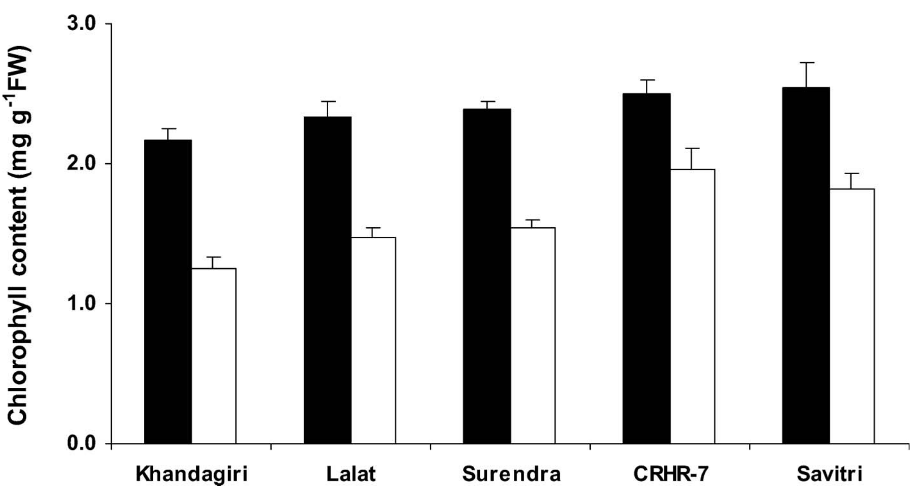

Figure 2. Chlorophyll content of fourth leaf from top at early ripening stage for SRI and CTS plants. Black and white bars represent SRI and CTS, respectively. Vertical bars represent the standard deviation ($n = 6$).

maintained a higher rate of photosynthesis than CTS plants. This reflects the delay in senescence of lower leaves of SRI plants and the maintenance of their greater activity during the ripening stage, an indication of actively utilizing light for greater dry matter production. Earlier, San-oh et al. (2006) also observed that hills with single seedlings maintained a higher rate of photosynthesis, more Rubisco content, and greater leaf nitrogen content than plants in hills with three seedlings. Lower levels of leaf chlorophyll and a lower photosynthesis rate in the short-duration compared to long-duration variety under both cultivation practices were responsible for the lower dry matter production in the former.

Root growth and activity

Experimental results showed a significant improvement in root growth in the SRI plants of all varieties (Table 5). With SRI management, two times more root dry

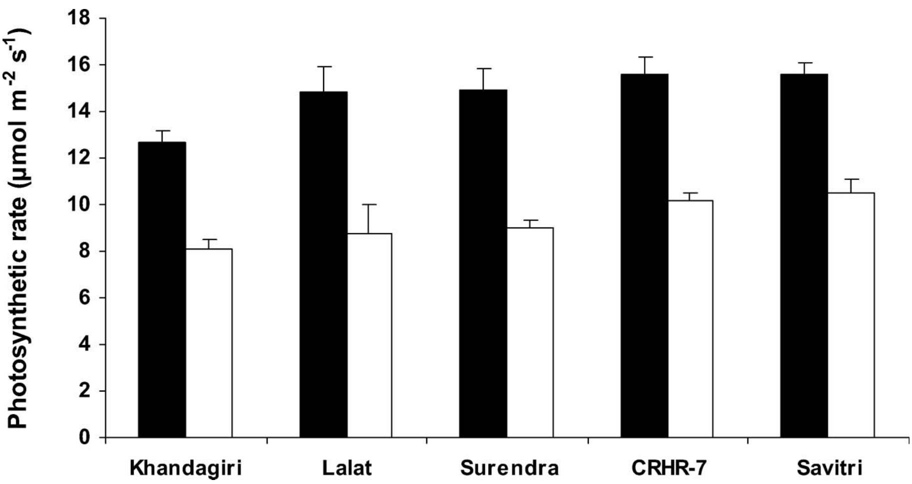

Figure 3. The rate of photosynthesis of fourth leaf from top at early ripening stage for SRI and CTS plants. Black and white bars represent SRI and CTS, respectively. Vertical bars represent the standard deviation (n = 6).

Table 5. Comparison of root dry weight (g) under SRI and CTS at the early ripening stage.

	Root dry weight (g hill^{-1})			Root dry weight (g m^{-2})		
Variety	SRI	CTS	Mean	SRI	CTS	Mean
Khandagiri	9.21	3.23	6.22	230.2	213.2	221.7
Lalat	11.45	4.55	8.00	286.1	227.3	256.7
Surendra	12.05	5.92	8.98	301.2	295.8	298.5
CRHR-7	13.22	10.35	11.79	330.6	258.8	294.7
Savitri	15.29	6.55	10.92	382.3	216.2	299.2
Mean (SRI change)	12.24	6.12	(100.0%)	306.1	242.3	(26.3%)
$LSD_{0.05}$						
Practice (P)		0.46			13.3	
Variety (V)		0.71			18.5	
P × V		1.00			26.2	

Table 6. Comparison of xylem exudation rates under SRI and CTS during early ripening stage.

Variety	Exudates amount ($g\ hill^{-1}$)			Exudates amount ($g\ m^{-2}$)			Rate per hill ($g\ hill^{-1}\ h^{-1}$)			Rate per stem ($g\ stem^{-1}\ h^{-1}$)			Rate per m^{-2} ($g\ m^{-2}\ h^{-1}$)		
	SRI	CTS	Mean	SRI	CTS	Mean	SRI	CTS	Mean	SRI	CTS	Mean	SRI	CTS	Mean
Khandagiri	4.87	1.60	3.24	121.8	105.6	113.7	0.20	0.07	0.13	0.45	0.42	0.43	5.07	4.40	4.74
Lalat	8.25	3.64	5.95	206.3	182.2	194.2	0.34	0.15	0.25	0.61	0.57	0.59	8.59	7.59	8.09
Surendra	9.89	4.13	7.01	247.3	206.3	226.8	0.41	0.17	0.29	0.73	0.67	0.70	10.30	8.60	9.45
CRHR-7	9.67	8.55	9.11	241.8	213.8	227.8	0.40	0.36	0.38	0.69	0.61	0.65	10.07	8.91	9.49
Savitri	9.89	6.45	8.17	247.3	213.0	230.1	0.41	0.27	0.34	0.62	0.57	0.60	10.30	8.87	9.59
Mean (SRI change)	8.51	4.88	(74.4%)	212.9	184.2	(15.6%)	0.35	0.20	(75.0%)	0.62	0.57	(8.8%)	8.87	7.67	(15.6%)
$LSD_{0.05}$															
Practice (P)		0.37			9.0			0.02			0.03			0.38	
Variety (V)		0.30			10.9			0.01			0.03			0.45	
P × V		0.43			15.4			0.02			ns			0.64	

ns, non-significant.

weight per hill indicates better root growth than in conventionally transplanted crop. Among the varieties, CRHR-7 and Savitri showed better root growth than the others. On a unit area basis also, the SRI crop had significantly more root dry weight (by 26.3%) than the crops grown with CTS. Among the varieties, root growth per unit area was similar for the Surendra, CRHR-7 and Savitri varieties.

Rice grown under standing water (CTS) creates hypoxic soil condition, and its roots degenerate under flooding, losing three-fourths of their roots by the time the plants reach the flowering stage (Kar et al. 1974). Unflooded conditions, combined with mechanical weeding, resulted in more air in the soil and greater root growth for better access to nutrients under SRI as compared with CTS. Such conditions would also support more aerobic soil biota.

Leaving wider spacing between plants in SRI (fewer plants per unit area) gives each more nutrients as roots have more adequate room to grow. Stoop et al. (2002) reported that SRI plants have deeper and stronger root systems, supported by intermittent irrigation practiced on soils without physical barriers to root growth. This effect is strengthened by having planted young, single seedlings at wide spacing and shallow in the soil. Other reports also confirmed that SRI plants have deeper root systems and larger roots compared to conventionally-grown rice plants (Tao et al. 2002; Satyanarayana et al. 2007). Younger rice seedlings have improved root characteristics like root length density and root weight after transplanting than do older seedlings (Mishra and Salokhe 2008).

Apart from better root growth under SRI, we also observed that SRI plants had more xylem exudation transported toward the stem during the early ripening stage and at a faster rate (Table 6). SRI plants showed significantly higher rate per hill, per stem and per unit area compared to CTS plants in all the varieties, with the lowest values in the short-duration variety Khandagiri.

Higher exudation rates in SRI plant roots indicate that the physiological activity of roots is high at the early ripening stage (Soejima et al. 1992, 1995) and that larger amounts of cytokinins are being transported from the roots, which helps in delaying leaf senescence (San-oh et al. 2006). Thus, in SRI plants we observed that greater root mass with higher activity delays leaf senescence, and in return, lower leaves supply more assimilates to keep roots more active during the ripening stage.

Conclusions

In the present study, we found that SRI methods produced higher grain yield compared to CTS, in all of the varieties tested. However, there was a pattern of response associated with plants' usual crop-cycle length. Yield enhancement was relatively greater for medium- and short-duration varieties with SRI as their percent increase with SRI management was higher than for long-duration varieties. With standard management as with SRI practice, high absolute levels of production were achieved but the latter had higher values.

The long-duration variety might have experienced some space constraints due to the standard protocol and possibly was not able to express its full potential in the present study. The higher grain yield produced by using single young seedlings with SRI was due to better dry matter partitioning, producing more grains and less straw.

The open-canopy structure of SRI plants with their higher LAI was able to intercept more light compared to plants grown with conventional transplanting methods. At the ripening stage, SRI plants had significantly more roots with higher activity, which were responsible for maintaining greater rates of photosynthesis of the lower leaves having delayed senescence. These features might have contributed to the improvements in yield components like grains/panicle, grain-filling percentage, and grain weight.

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