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A CRITICAL ASSESSMENT OF THE IMPORTANCE OF SEEDLING AGE IN THE SYSTEM OF RICE INTENSIFICATION (SRI) IN EASTERN INDIA

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SUMMARY

A survey of the system of rice intensification (SRI)-related literature indicates that different authors have drawn conflicting inferences about rice yield performances under the SRI, chiefly because the SRI methodology has been variously advocated, interpreted and implemented in the field using different rice varieties, seedling ages at transplantation, cultivation seasons and nutrient management regimes. In particular, the SRI method of single-seedling transplantation (SST) has potential economic advantage due to reduced seed costs, but it is not clear whether SST is an effective management strategy across a range of seedling ages, and whether there is any specific seedling age that is optimal for yield improvement of a given rice variety. This is an important consideration in rain-fed ecosystems where variable rainfall patterns and lack of controlled irrigation make it difficult to reliably transplant at a specific seedling age as recommended for the SRI. We conducted a five year-long experiment on a rain-fed organic farm using a short-duration upland and a medium-duration lowland landrace, following the SRI methodology. Rice seedlings of different ages (6, 10, 14, 18 and 28 days after establishment) were transplanted at 25 cm × 25 cm spacing in three replicated plots. The performance for each landrace was examined with respect to productive tillers, panicle density, total grain counts per hill and grain yield per unit area. Performances of seedlings of different ages were compared with that of control plots that employed all SRI practices with the exception that 28-day-old seedlings were transplanted with three seedlings per hill. The results indicate that (1) the SRI can improve mean panicle density if seedling age $\leq$ 18 days, but that responses differ between varieties; (2) the number of productive tillers per hill is significantly less in SST than that of multiple seedling transplants (MST) of 28-day-old seedlings of both upland and lowland varieties; (3) the total grain numbers per hill of the lowland variety is significantly greater for 14-day-old SST than 28-day-old MST; (4) the grain yield per unit area from young SRI transplants is significantly greater than that from 28-day-old MST for the lowland variety, although the magnitude of the improvement was small; (5) for the upland variety, grain yields declined with the oldest seedlings, but planting multiple seedlings per hill made the yield of the oldest transplants on par with that of younger seedlings planted singly. Our findings suggest that transplanting younger seedlings under the SRI management may not necessarily enhance grain yields.

INTRODUCTION

The system of rice intensification (SRI) has evoked considerable interest among agronomists over the past few years, and posed interesting research questions in plant physiology. The SRI essentially comprises the following methodological components (McDonald *et al.*, 2008; Stoop *et al.*, 2002; Uphoff, 2003):

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1. Shallow (1–2 cm) transplanting of young (< 16-day-old, or before the fourth phyllochron) seedlings without delay into a moist but not flooded seedbed.
2. Transplanting of single seedlings at wide (25 cm × 25 cm to 30 cm × 30 cm) spacing (with plant density not exceeding 16 m^{-2})
3. Alternation of wetting and drying of the field during vegetative growth.
4. Low nutrient input in an organic form (e.g. compost).

This technique drastically reduces seed and water requirements but increases the growth of weeds, which need frequent removal. Nevertheless, SRI seems to have several advantages for farm economies in terms of substantial saving on the expenditure of seeds, nutrient inputs and water (Uphoff, 2003; Uphoff *et al.*, 2002), and is thus considered to be superior in resource-poor farms to the conventional practice (Dobermann, 2004). The higher labour cost for weed control is reported to be more than offset by significantly greater grain output (Nissanka and Bandara, 2004; Uphoff, 2003).

Although claims of miraculous yields (e.g. 15–23 t ha^{-1} by Rafaralahy, 2002) have been critiqued (Dobermann, 2004; Horie *et al.*, 2005; Sheehy *et al.*, 2004), the overall effect of SRI on grain output, reported from over 20 countries – from Cuba to China and from Gambia to South Asia – is impressive (Stoop *et al.*, 2002; Uphoff, 2003; Uphoff *et al.*, 2008). Most studies report profuse emergence of tillers from each seedling after transplanting, and a remarkable increase in grain yield, which constitutes a 'standard claim' of SRI proponents. However, in recent years, substantial skepticism about the standard claim has surfaced among crop scientists. A few researchers have found no significant difference in rice yield between SRI and conventional best practices (McDonald *et al.*, 2006, 2008; Sheehy *et al.*, 2004; Sinclair and Cassman, 2004), and assigned the reports of high grain output from SRI to 'unconfirmed field observations' (UFOs) (Sinclair and Cassman, 2004) and/or measurement error (Sheehy *et al.*, 2004, 2005). Although this critique has been contested on methodological and empirical grounds (Thakur *et al.*, 2010b; Uphoff *et al.*, 2008), it seems that different standards of experiments adopted by different researchers pose a formidable methodological debacle to establishing conclusive evidence in favour of an SRI advantage. Furthermore, some of the studies examining SRI effects on rice yield did not strictly follow SRI methodologies, as their SRI treatments included transplanting of two seedlings per hill (Latif *et al.*, 2005); higher seedling density ($\geq$25 m^{-2}) at transplanting (Pasuquin *et al.*, 2008; Senthilkumar *et al.*, 2008; Thakur *et al.*, 2010a) and use of synthetic fertilisers without compost (Mahender Kumar *et al.*, 2010; Pasuquin *et al.*, 2008; Senthilkumar *et al.*, 2008; Sinha and Talati, 2007) or with compost (Menete *et al.*, 2008; Thakur *et al.*, 2010a). Overall, the published studies do not seem to tease out the different plausible factors contributing to grain yield increase, and raise several methodological questions that still remain inadequately answered:

1. Does single seedling transplanting (SST) alone, regardless of or in combination with young ages of seedlings, have any significant effect on the proportion of productive (panicle-bearing) tillers?

2. What is the optimum seedling age at transplanting to achieve the best grain yield?
3. Which type of rice genotype is the most likely to significantly improve yield under SRI?

The first question arises because no controlled experiment has established the effect of single-seedling transplanting (SST – an essential component of SRI) vs. conventional multiple-seedling transplanting (MST) on yield components for a specific type of rice cultivar. Regarding the second question, most researchers have conducted experiments with an arbitrarily selected seedling age at transplanting between 8 days and 16 days. For example, in Sumatra, McHugh (2002) recorded the highest yields from 10-day-old transplants, while Makarim *et al.* (2002) reported that 15-day-old transplants out-yielded 21-day-old transplants. Krishna and Biradarpatil (2009) observed higher grain yields with 12-day-old transplants than 8-, 16- and 25-day-old transplants. In Thailand, 12-day-old transplants consistently out-yielded 30-day-old transplants (Mishra and Salokhe, 2008). In India, both Mahender Kumar *et al.* (2010) and Thakur *et al.* (2010b) recorded higher yields from SRI plots planted to 12-day-old seedlings compared with 25-day-old transplants. Thus, taken together, it is hardly possible to ascertain whether transplanting at a particular seedling age (say 12 days) is likely to increase either productive tillers or grain yields compared with another seedling age (say 10 or 16 days) in all countries.

The third point at issue is that different investigators in different countries have employed different rice varieties; neither the critical evaluations of SRI (e.g. Sheehy *et al.*, 2004) use the same cultivars as those used in the studies they contest nor do they compare yield performances of different cultivars under the same experimental conditions. Published studies have almost always examined photoperiod-insensitive cultivars, and all of these are modern hybrid or elite 'high-yielding' varieties grown on irrigated farms. The only exception we found is a study by Tsujimoto *et al.* (2009), where local and locally improved varieties were used, but their comparison with the SRI and conventional farming systems involved different varieties on different study sites. Thus, such studies fail to make it clear whether the rice yield increase or decrease was influenced by the selected rice genotype compared with others.

The selection of the cultivar is also important in SRI testing because different rice varieties have different degrees of tolerance to water stress. Upland-adapted local landraces tend to be more water-stress-tolerant than modern hybrids and the landraces adapted to flooded soils (Atlin, 2006; Deb, 2005). Indeed, moderately drought-tolerant cultivars are known to be appropriate for aerobic rice cultivation in Asia (Atlin *et al.*, 2006; Farooq *et al.*, 2009). It is therefore not clear whether the less water demand of rice plants reported in the SRI literature is a consequence of the selection of cultivars that are adapted to water stress.

Thus, amidst the wide range of experimental materials and standards employed in the SRI research in different countries (McDonald *et al.*, 2008; Stoop *et al.*, 2009), there is no published literature to enable one to compare grain yields between different rice genotypes and ages of seedling on SRI farms. With an aim to bridge this gap of understanding, we undertook the present study over a period of five years using two different rice landraces and different seedling ages at transplanting. We compare the effects of seedling age at transplanting on tillering abilities, number of grains per panicle (panicle density), grain counts per hill and yield per unit of land area for two landraces in rain-fed condition.

MATERIALS AND METHODS

Study site and plot management

Experiments were conducted from 2005 to 2009 on 1.2 acre of Basudha farm (www.cintdis.org/basudha), located in the district of Bankura, West Bengal, India (23° 12′ 25.6″ N, 8723° 12′ 25.6″ N, 16′ 54.3″ E). The area is characterised by undulated lateritic terrain with contiguous dry upland and lowland paddy fields.

Basudha farm's topsoil is sandy clay (44% sand, 52% clay, 4% silt) on oxisol substrate. Soil samples were collected at the end of the 1994–1995 cropping cycle, and tested using standard methods cited by the Government of India (2011). The farm soil has a mean pH of 6.1, and electrical conductivity (EC) = 0.16 ms cm^{-1}. The organic matter content (Walkley–Black) of the soil was 3.3%, available nitrogen 226 kg ha^{-1}, exchangeable potassium (NH_4O-acetate) 94 kg ha^{-1} and available phosphorus (Olsen) was 3.8 mg kg^{-1}.

The farm received no synthetic agrochemicals for the past 15 years. At the onset of each cropping cycle, all plots and nursery beds were treated with composted cattle manure (equivalent nitrogen content was 12 g m^{-2}) at 400 g m^{-2}, 80 g m^{-2} of green manure and 20 g m^{-2} of rock phosphate (20% P_2O_5), inoculated with phosphorus solubilising bacteria (*Pseudomonas* spp.). Weeds were manually removed thrice a year (mid-July, early August and mid-September) from all beds.

Season of cultivation and selection of cultivars

In eastern India and Bangladesh, the principal season for the cultivation of rice is the monsoon season (June –October), and most rice farms in the region are rain-fed (Government of West Bengal, 2009; Pandey and Pal, 2007). Since the introduction of the Green Revolution in the late 1960s, cultivation of semi-dwarf *boro* (summer) rice with high harvest index has intensified rice production in irrigated farms (Fujita, 2010). The semi-dwarf, photoperiod-insensitive, high input-responsive Green Revolution varieties are cultivated in both wet and dry seasons (International Food Policy Research Institute (IFPRI), 2002; Mishra, 2002). Nevertheless, *aman* (winter-harvest) rice, grown in the period June–December, contributes to a major portion of rice production in the region (Fujita, 2010; Government of West Bengal, 2009). Most traditional *aman* varieties are photoperiod-sensitive tall landraces, cultivated on both lowland (bunded paddy) and upland (rain-fed dryland) farms. Our use of the terms 'upland' and 'lowland', in conformity with the standard description of Asian rice production ecosystems, refer to the poor and high water holding capacity of paddy farms, respectively, and 'have no relation with the elevation or topography where the rice is grown' (Linquist *et al.*, 2006: 29).

Basudha farm is a mosaic of rain-fed upland and lowland fields. For rain-fed upland plots, we chose Tulsa, a short duration (98 days) landrace. Shiuli, a medium duration (130 days) landrace, was selected for rain-fed lowland plots. Agronomic and morphological characteristics of both these varieties are described in Deb (2005)[1]. Contingent on the arrival of the monsoon rain, rice seeds were sown in the first week of July in 2005, and a week later in subsequent years. Young seedlings of different ages (6–28 days after germination) were transplanted in discrete batches to the experimental plots adjacent to the nursery.

Design of the study

Seeds of both varieties were directly sown on puddled seedbeds, and the age of seedlings was counted from the day of their germination. Thus, all transplant ages expressed here in number of days denote days after establishment of germinated seedlings in nursery beds. In the first year of the experiment (2005), three replicated plots of Shiuli (adapted to rain-fed lowland) and three replicated plots of Tulsa (adapted to rain-fed upland) were randomly selected on Basudha's organic farm. For each cultivar, three replications of eight beds, each bed of 2 m × 2 m size, were planted to 6-, 8-, 10-, 12-, 14-, 16-, 18-, and 28-day old seedlings. The rationale for our inclusion of the 28-day transplants is that transplanting of seedlings of ≥28 days is the long-standing practice throughout eastern India (Fujita, 2010; Pandey and Pal, 2007). On each plot of our experiment, all seedlings were planted singly, at 25 cm × 25 cm spacing (16 hills/m^2). Our experimental design was in full conformity with the SRI protocol as stipulated in Stoop *et al.* (2002) and Uphoff (2003), and included different seedling ages at transplanting for comparison. From each bed, 24 hills (three random hills from each row) were semi-randomly selected for harvest. All panicles from the selected hills were examined for enumeration of mean number of grains per panicle (panicle density), total grain count per hill (TG) and yield (total grain weight per unit area).

The data of the first year (2005) were analysed to detect the difference between the means of productive tillers per hill (PT), number of grains per panicle (or panicle density, PD), TG and yield among different seedling ages for each rice variety. A homogeneity χ^2 test ($\chi^2 = 25.8$, df $= 23$) confirmed homogeneity of data from the replicated beds planted to the eight seedling ages at transplanting from both varieties. Results of sequential pairwise *t*-tests between the means of PD, TG and yield (g m^{-2}) of all seedling ages at transplanting are given in Table 1, which indicates the following:

[1]Morphological characteristics relevant to the selection of rice varieties in this study are as follows:

Landrace	Duration (d)	Mean panicle density	1000-grain weight (g)	Grain shape	Special characteristics
Shiuli	130	233	32.8	Long bold	
Tulsa	98	112	15.9	Short bold	Moderately drought-tolerant

Table 1. Matrix of difference between means of panicle density (PD), total grain count per hill (TG) and yield (YD) for the lowland variety Shiuli (upper diagonal) and the upland variety Tulsa (lower diagonal) for the first year of study (2005).

Transplant age (days)	6	8	10	12	14	16	18	28
6			*PD* *YD*	*PD* *TG*	*PD* *TG* **YD**	*TG* *YD*	*PD*	*PD* *TG* **YD**
8					*TG* **YD**	*PD* *TG* *YD*	**TG** *YD*	*TG* *YD*
10	**TG** *YD*	*PD* **YD**			*PD* **TG**	*TG* **YD**	*PD* *TG* *YD*	*TG* *YD*
12	*PD* *TG* *YD*	**PD** **TG** *YD*	*PD*			*TG* **YD**	*TG* *YD*	**TG** **YD**
14	*TG* *YD*	*PD* **TG** *YD*	*PD* ***TG*** ***YD***			*PD*	*TG* *YD*	*PD* *TG* **YD**
16	*PD*	*PD* *TG* **YD**	*PD* **TG** *YD*	TG **YD**				*TG* *YD*
18	*TG* **YD**	*TG*	*PD* *YD*	*PD* *TG* **YD**	*TG* *YD*			
28	**PD** **TG** *YD*	*PD* *TG*	*PD* **YD**	**TG** *YD*	*PD* **TG** *YD*	*YD*		

Note: Letters in italics denote significance of difference (two-tailed test) at $p < 0.05$. Letters in boldface at $p < 0.01$. Blank spaces in cells indicate no difference.

1. There was no significant difference ($p > 0.1$) in PD and TG when compared between their means for transplant ages ∈ (6 and 8 days), (10 and 12 days), (14 and 16 days), (16 and 18 days) and (18 and 28 days) for both the varieties.
2. Significant differences existed between means of TG and yield for transplant age (6, 8, 10, 12, 14 days) and for the age of 28 days.
3. The Means of PT varied between different seedling ages and between the rice varieties. The variability of the tiller numbers was too large for any seedling age to discern any definite trend.
4. The Means of grain yield (in weight per unit area) for transplant ages ∈ (6, 8, 10, 12, 14, 16 days), compared to that for 28 days was significantly different for both varieties.

Guided by these preliminary findings, 8-, 12- and 16-day old transplants were not repeated in the next phase of our study. In the subsequent four crop cycles, from 2006 to 2009, Tulsa and Shiuli rice seedlings were transplanted separately in four plots (with three replications), with each plot assigned to a discrete seedling age – 6-, 10-, 14- and 28-day-old seedlings for Tulsa, and 10-, 14-, 18- and 28-day-old seedlings for

Shiuli. Following the SST technique of the SRI, seedlings of all ages were transplanted with single seedlings per hill. In addition, a plot for MST for 28-day-old transplants, with three replications, was also maintained for each variety. The 28-day MST plots, planted with three to four seedlings per hill, represent the conventional rice farming practice of eastern India. Each plot measured 2 m × 2 m, planted to 64 hills in eight rows and eight columns at 25 cm × 25 cm spacing. Thus, the planting density was the same (16 hills m^{-2}) for all seedling ages in all years and for both SST and MST.

A structured random sample of 11 hills (comprising two randomly chosen hills from either the first or second row, and three randomly chosen hills from each of three alternate rows) was selected and marked, and the number of PT of each selected hill was counted after flowering. At maturity, all (primary, secondary and tertiary) panicles from each selected hill were harvested for enumeration of grains. Thus, the total number of panicles that were sampled and counted over the four years of study was as follows: [2 (cultivars) × {(4 (seedling ages SST) + 1 (28-day MST)} × 11 (hills) × n (panicles/hill) × 3 (replications) × 4 years] = 1320 n , where n represents the mean number of panicles per hill, ranging between 7 and 12, varying with year and treatment. Mean PD and mean TG were estimated from manual counting of grains of all sampled panicles from each plot. From each of the 1320 hills, a sample of 100 grains was weighed on a digital balance, and the mean 100-grain weight (MGW) was determined for each treatment from 100-grain weights from three replicate plots. Yield from each plot was calculated as the product of hill density (No. m^{-2}), mean TG (No. $hill^{-1}$) and MGW (g):

$$\text{Yield}\,(\text{g}\,\text{m}^{-2}) = (16 \times \text{TG} \times \text{MGW})/100.$$

All sampled panicles are preserved in our laboratory for re-examination/verification by SRI researchers.

Statistical analyses

Statistical comparisons between treatment beds (among all seedling ages) were based on PT, TG and PD and yield data, obtained from three spatial replicates of each experimental treatment in respect of rice variety and seedling age.

After 2005, all experimental treatments, farm plot locations and the farm conditions were identical in the subsequent four years (from 2006 to 2009). The experiments over the four years may therefore be considered as four temporal replications of the experiment. These experiments were repeated each year afresh with the same design and protocol with replicated plots so that each experimental unit sampled independently in successive years constitutes a genuine temporal replication and not pseudoreplication (Hargrove and Pickering, 1992; Underwood, 1997). Accordingly, all PT, PD, TG and yield data from spatial replicates collected over four years were aggregated and subjected to a Student–Newmann–Keuls test for normality of distribution. The aggregate data showed that their distribution was not normal, and therefore Student's t-test was obviated. Instead, a Mann–Whitney U test was

Table 2. Year-wise comparison of total grain count per hill (TG), panicle density (PD), number of productive tillers (PT) and grain yield (YD) for different seedling ages at transplanting.

	2006				2007				2008				2009			
SAT	TG	PD	PT	YD	TG	PD	PT	YD	TG	PD	PT	YD	TG	PD	PT	YD
Rice variety: Shiuli																
10 SST	2119	191	11	555	1281	141	9	493	972	115	8	422	1139	157	7	402
14 SST	2214	190	12	637	948	95	10	720	1164	129	9	514	1122	164	7	481
18 SST	2214	197	11	612	1300	143	9	518	1001	134	8	362	1118	144	8	410
28 SST	1856	191	10	434	1201	134	9	435	890	111	8	357	1123	145	8	408
28 MST	1561	149	11	423	1217	127	10	440	964	119	8	363	1324	128	10	453
Rice variety: Tulsa																
6 SST	601	102	6	189	1372	137	10	384	760	104	8	217	1339	179	8	570
10 SST	747	119	6	241	1485	134	11	446	756	127	6	255	1208	183	7	566
14 SST	1013	128	8	292	1263	138	9	354	849	121	7	251	1108	157	7	373
28 SST	504	77	6	179	793	133	6	239	655	115	6	174	1224	157	8	395
28 MST	1038	112	9	273	932	101	9	291	533	80	7	171	1326	158	9	483

Note: SAT = seedling age (days) at transplanting. Values are rounded up for brevity.

performed, with 95% confidence interval (CI). All PT, TG, PD and yield data for each treatment shown here are the mean values over all spatial and temporal replicates over four years.

RESULTS

A summary of the mean number of panicles per hill (or PT), PD, TG and grain yield (g m^{-2}) from all replications for each year are given in Table 2, and discussed under separate rubrics.

Overall, the PD, TG and yield figures are considerably less for the short-duration upland rice variety Tulsa than for the medium duration lowland variety Shiuli. However, the mean PT for young seedlings was consistently lower for all SST treatments of all seedling ages than for the conventional 28-day MST (henceforth shorthanded as 'the MST'). The yearly fluctuations in PD, TG and yield in both rice cultivars seem to be influenced by variations in monsoon precipitation (Figure 1), but examination of this relationship is beyond the scope of this study.

Yield characteristics in the rain-fed upland variety Tulsa

(1) The mean panicle density of SST 28-day transplants was significantly greater than that of the MST transplants (Table 3).
(2) There was no difference in TG between transplants of age 6 days and 28 days, but the TG for 10- and 14-day transplants were significantly greater than 28-day transplants (Table 4).
(3) None of the SST plots were any different from the MST plots in TG counts (Tables 3 and 5).
(4) There was no difference in PT between 6-day and 10-day transplants, but PT of 14-day transplants were significantly more numerous than that of 28-day

Table 3. The effect of transplanting method (SST vs. MST) with 28-day-old rice plants on the number of productive tillers per hill (PT), total grain count per hill (TG), panicle density (PD) and grain yield (YD). Relationships that are statistically not significant ($p > 0.05$) are not shown.

	Upland rice (Tulsa)	p	Lowland rice (Shiuli)	p
PT	28-day MST > 28-day SST	0.000	28-day MST > 28-day SST	0.000
TG				
PD	28-day SST > 28-day MST	0.000	28-day SST > 28-day MST	0.001
YD	28-day MST > 28-day SST	0.03		

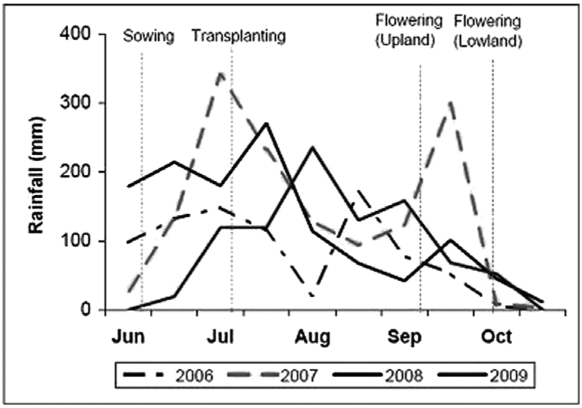

Figure 1. Variation over the period from 2006 to 2009 in the amount of precipitation on Basudha farm.

transplants (Table 4). However, the MST produced significantly more PT than 6-, 10- (Table 5) and 28-day transplants (Table 3).

(5) Grain yield (g m^{-2}) for 6-, 10- and 14-transplants was significantly higher than 28-day transplants (Table 4), but the yields from these SST plots were statistically no different from the conventional MST (Table 5). The yield of 28-day SST was significantly less than that of the MST (Table 3).

Yield characteristics in lowland variety Shiuli

(1) The mean panicle density from 28-day SST was significantly greater than that from the MST plots (Table 3). However, TG and yield of the MST were no different from 28-day SST (Table 3), indicating that the absolute number of grains per hill for older (>20 days) seedlings is unlikely to be influenced by the method of transplanting (SST or MST).
(2) The mean panicle density did not show any significant difference between 10-day and 14-day plots, but was significantly greater for 14-day than for 18- and 28-day transplants (Table 4).
(3) The number of productive tillers was significantly less for 28-day transplants than for all younger transplants (Table 4), and also less than the MST (Table 3).
(4) The total grain count per hill showed no significant difference among 10-, 14- and 18-day transplants, all of which were significantly greater than TG for

Table 4. Comparison of effects of seedling age on the number of productive tillers per hill (PT), total grain count per hill (TG), panicle density (PD) and grain yield (YD) for all SST treatments. Relationships that are statistically not significant ($p > 0.05$) are not shown.

	Upland rice (Tulsa)	p	Lowland rice (Shiuli)	p
PT	14 day > 28 day	0.003	10 day > 28 day	0.009
			14 day > 28 day	0.000
			18 day > 28 day	0.011
TG	10 day > 28 day	0.039	10 day > 28 day	0.011
	14 day > 28 day	0.001	14 day > 28 day	0.000
			18 day > 28 day	0.008
PD	10 day > 28 day	0.093	14 day > 28 day	0.040
			14 day > 18 day	0.041
YD	6 day > 28 day	0.04	10 day > 28 day	0.011
	10 day > 28 day	0.000	14 day > 28 day	0.000
	14 day > 28 day	0.000	18 day > 28 day	0.008
			14 day > 10 day	0.000
			14 day > 18 day	0.000

Table 5. The effect of seedling age with SST on the number of productive tillers per hill (PT), total grain counts per hill (TG), panicle density (PD) and grain yield (YD) compared with conventional MST of 28-day-old seedlings. Relationships that are statistically not significant are not shown.

	Upland rice (Tulsa)	p	Lowland rice (Shiuli)	p
PT	6-day < 28-day MST	0.045	18-day < 28-day MST	0.038
	10-day < 28-day MST	0.001		
TG			14-day > 28-day MST	0.01
PD	6-day > 28-day MST	0.011	10-day > 28-day MST	0.000
	10-day > 28-day MST	0.000	14-day > 28-day MST	0.000
	14-day > 28-day MST	0.000	18-day > 28-day MST	0.000
YD			10-day > 28-day MST	0.05
			14-day > 28-day MST	0.000
			18-day > 28-day MST	0.021

28-day (Table 3). TG for 14-d transplants was significantly different from the MST (Table 5).

(5) Plots with 10-, 14- and 18-day transplants produced significantly more PT, TG and yield than SST 28-day transplants (Table 4).

(6) Grain yield for 14-day transplants was greater than 10-, 18- and 28-day transplants (Tables 4 and 5).

The only yield component that was significantly better in the conventional (28-day MST) plots than in SST plots with both young and old transplants of the upland variety Tulsa is the mean number of PT (Tables 3 and 5). MST 28-day transplants produced significantly more tillers than 18-day-old Shiuli transplants (Table 5). In contrast, SRI plots with young transplants of Shiuli produced significantly more tillers than SST 28-day plots (Table 4). A strong positive relationship holds between PT and

Table 6. Regression of total grain count per hill (TG) on productive tillers (PT).

Saeedling age (days) at transplanting	Slope	Constant	*r*	*t*
Lowland variety Shiuli				
10	161.80	67.35	0.81	5.10*
14	154.56	62.48	0.86	6.20*
18	189.79	325.24	0.84	5.74*
28	128.24	112.80	0.78	4.61*
28 MST	130.77	13.15	0.79	4.82*
All treatments	159.64	104.01	0.81	5.10*
Upland variety Tulsa				
6	120.57	99.30	0.87	6.48*
10	119.02	94.02	0.87	6.48*
14	119.63	43.20	0.77	4.48*
28	139.43	89.62	0.78	4.67*
28 MST	120.24	74.63	0.71	3.74*
All treatments	120.34	40.80	0.81	5.10*

* $p < 0.01$.

TG across all seedling ages and within the two 28-day groups (SST and MST). The effect seems to be consistent in both the cultivars under study (Table 6).

DISCUSSION

This study examines, for the first time, the effect of SRI practice on yield characteristics of two traditional photoperiod-sensitive landraces, repeated over four seasons. We examine here the standard SRI claims of increased number of PT and grain yields under separate rubrics. We then critically discuss the effects of various components of the SRI methodology – (a) single transplanting of (b) young seedlings, and posit our study in the light of previous experimental findings.

Productive tiller numbers

The panicle density, conjointly with PT determines the absolute grain yield on any farm. Thus, high yields are associated with large numbers of spikelets per unit area (De Datta, 1981), which rice scientists and farmers seek to achieve by using high plant densities (directly seeded or transplanted in clumps). However, stresses occurring during the later growth stages cause 2 to 50% tiller mortality, and unfilled spikelets, which normally are about 15% at harvest (Kropff *et al.*, 1994). The SRI practices may preclude such stresses by early transplanting of seedlings before the onset of the tillering process (Stoop *et al.*, 2002), leading to a positive correlation between PT and TG. In our study, the correlation of TG with PT is uniformly strong in all treatments with young seedlings as well as with conventional transplantation of 28-day-old seedlings (Table 6), indicating that PT does not significantly depend on seedling age at transplanting.

Profuse tillering ($>$50 hill^{-1}) is often reported from SRI farms (de Laulanie, 1993; Stoop *et al.*, 2002; Uphoff, 2003). Profuse tillering may be detrimental to grain production if the proportion of non-productive tillers is also high. A greater proportion of non-productive tillers may result in grain yield reduction, owing to high respiration cost and dry matter loss (Horie *et al.*, 2005; Schnier *et al.*, 1990). However, SRI seems to reverse this relationship, and most of SRI studies report greater frequency of PT associated with greater grain yield. Stoop *et al.* (2002) report that with 25 cm × 25 cm or wider spacing of transplants, 'farmers in Madagascar using SRI methods most skillfully can produce plants with more than 100 fertile tillers; the highest number reported is 140'. More modest means of 17.9 and 18.8 per hill, respectively, were reported by Thakur *et al.* (2010a) and Thakur *et al.* (2010b) at 25 cm × 25 cm spacing on their modified SRI plots. At the same spacing, rice plants on our SRI plots generated an overall mean of 9.7 PT per hill for Shiuli, and 7.7 PT per hill for Tulsa, both in rain-fed condition. The highest mean PT was 10.9 for Shiuli in 2006, and 9.1 for Tulsa in 2007.

Our data thus do not conform to the standard report (de Laulaníe, 1993; Gani *et al.*, 2002; Thakur et al., 2010a, b; Uphoff, 2003) of an enhanced tillering effect in SRI. On the contrary, PT is significantly greater on the MST plots than the SRI plots planted with 6- and 10-day-old seedlings of Tulsa, and 18-day-old seedlings of Shiuli (Table 5 and Figure 2), indicating that SRI does not seem to have any favourable effect on PT, for at least the rice varieties under study. The reason for this non-conformity to the previously reported SRI results is that the landraces, Shiuli and Tulsa, used in our study were not traditionally selected or bred for high tillering ability. As the tillering ability differs between rice varieties, 'those varieties which have high tillering ability perform better as compared to the shy tillering ones' under SRI method (Mahender Kumar *et al.*, 2010: 64). The SRI method would not significantly enhance the tillering ability of Shiuli, Tulsa and many other inbred varieties that are not selected for this characteristic. Rather, SST would tend to reduce the number of PT per hill in the landraces examined.

Grain yield

Our study seems to corroborate the standard claim of significant yield increase with early transplantation (Pasuquin *et al.*, 2008; Stoop *et al.*, 2002; Uphoff, 2003; Uphoff *et al.*, 2008), but does not corroborate any miraculous yield improvement. As Figure 3 shows, transplanting of 10-, 14- and 18-day-old seedlings of the lowland variety Shiuli had a significantly positive effect on both PD and yield compared with conventional MST 28-day transplants. However, the effect disappeared in the upland variety Tulsa, whose younger transplants showed no difference from the MST in both TG and yield (Table 5 and Figure 2).

The standard recommendation in the SRI literature (e.g. de Laulaníe, 1993; Stoop *et al.*, 2002; Uphoff, 2003) is to transplant seedlings between 8 and 16 days, implying absence or uncertainty of the effect of transplants younger than 8 days. However, Gani *et al.* (2002) and Pasuquin *et al.* (2008) found that 7day-old transplants also produced early tillering and higher yield than 21-day-old transplants. Our study shows that for the upland variety Tulsa, grain yields of younger transplants of ages between 6 and 14 days are no better than that of the MST, while young transplants of Shiuli yield

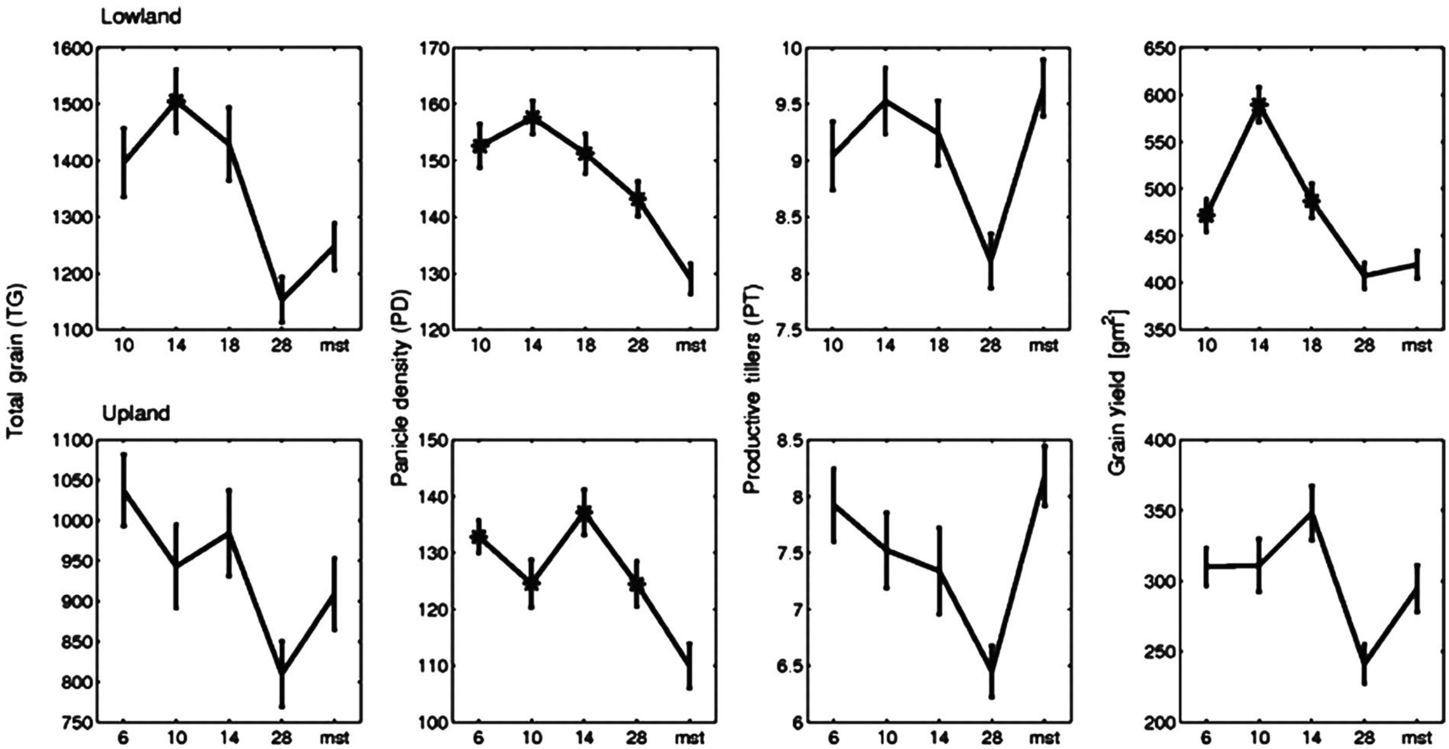

Figure 2. Mean grain numbers per hill (TG), panicle density (PD), productive tillers (PT) and grain yield (g m^{-2}) for traditional rice varieties adapted to rain-fed lowland (top) and upland (bottom) farms. Abscissae show seedling ages (in days), with MST denoting multiple transplants of 28-day-old seedlings. Vertical bars represent standard errors. Values that are significantly different from that of MST are marked with an asterisk.

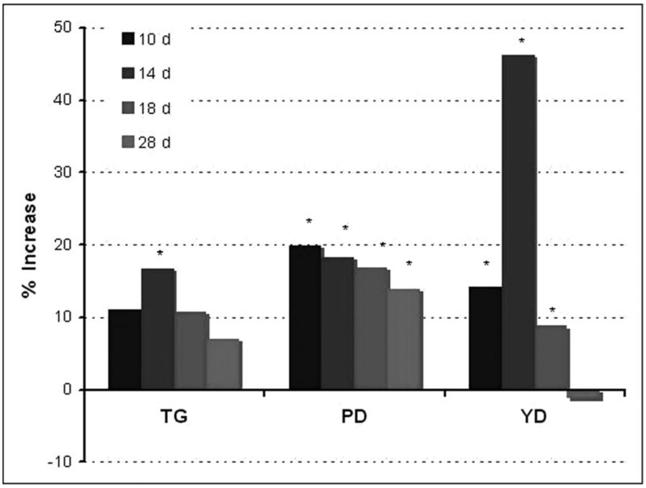

Figure 3. The effect of single-seedling transplanting of the lowland variety Shiuli with different transplant ages on grain numbers per hill (TG), panicle density (PD) and grain yield (g m^{-2}) compared with the conventional MST. Each column shows the median value of all spatio-temporal replicates for a transplant age. An asterisk indicates significant difference from MST.

better than both MST and SST 28-day-old transplants (Tables 4 and 5). It seems likely that the extent of the effect of seedling age at transplanting on yield differs with varietal genotypes (Pasuquin *et al.*, 2008), which might explain the variability of effects of transplant age of <8 days.

The effect of SST on yield components

Transplantation of single seedlings with wide spacing is an essential component in SRI, and is thought to be a significant determining factor for tillering and grain yield improvement, even for conventional seedling age of >26 d (Horie *et al.*, 2005; San-Oh *et al.*, 2004). Our study, however, shows that with 28-day-old seedlings, SST seems to be of no advantage over MST in terms of PT, TG, PD and yield for the upland variety Tulsa (Figure 2). Rather, the yield of MST was greater than SST for 28-day transplants of Tulsa (Table 3). Furthermore, PT of MST plots was significantly greater than that of most SST plots for both varieties in this study (Tables 3 and 5). However, PD and yield of the lowland variety Shiuli was significantly greater for all young transplants under SRI than that of the MST (Figure 3).

In this study, all SRI plots with SST produced significantly greater PD than the MST plots for both upland and lowland varieties (Tables 3 and 5). Conversely, SST plots with 28-day-old seedlings produced significantly less PT than MST plots (Table 3), indicating that SST may suppress tillering, possibly resulting in a yield drag, in old transplants. Furthermore, 28-day SST and MST plots showed no difference in TG counts for both rice varieties (Table 3). This finding is consonant with the findings of Oziegbe and Faluyi (2007) with 21-day-old seedlings, and of Miah *et al.* (2004) with 26-day-old seedlings, planted at the same spacing. Moreover, yield decline was also reported for SST of 26-day-old (Prasad and Sheer, 1992) and 30-day-old (Rahman *et al.*, 2007) seedlings of different rice cultivars in spite of adequate nitrogen availability in soil.

The effect of early transplantation

Some early experiments in Japan recorded a positive effect of early (≥10 days) transplanting on grain yield, although these studies did not consider other components of SRI (Horie *et al.*, 2005). Our results (Table 4 and 5) show that the early age of seedlings at transplantation seems to be consistently conducive to grain yield enhancement.

However, when the TG and PD data are examined separately for years, the effect of early age of seedlings is not prominent, especially in the years of late monsoon arrival (2006 and 2009). For photoperiod-sensitive rice varieties, the younger the seedlings at transplanting, the longer the time to heading and maturity. Therefore, in places where growth duration is affected by temperature and/or availability of water, 'young seedlings do not have enough time to express their potential' (Horie *et al.*, 2005: 267). Nevertheless, Tables 4 and 5 show a consistent advantage of early transplanting in TG and grain yield over 28-day-old transplants on SST plots. In contrast, conventional transplantation of multiple old seedlings tends to engender significantly more PT than SRI transplants, especially the 6- and 10-day-old transplants of Tulsa (Table 5). For Shiuli, none of the SST plots produced more productive tillers than the MST (Table 3 and 5), but within the SRI plots, the mean PT of younger transplants was significantly greater than that of 28-day-old transplants (Table 4).

The role of water management

Scanty rainfall in low-rainfall districts and the late arrival of the monsoon rain constitute water stress for the rice plant, affecting its yield characteristics (Sarvestani *et al.*, 2008). It is plausible that fluctuations in rainwater availability around vegetative and panicle initiation stages of the rice plants (Figure 1) might have influenced the observed variability of grain outputs on both the SRI and MST plots in our study. However, our study was not designed to ascertain the effect of water availability on SRI, nor would the comparable datasets for only four years of our study period allow us to infer any relationship.

The role of soil nutrients

Soil nutrient level is an important factor for high yielding response of rice (Rahman *et al.*, 2007). Proponents of SRI have attributed the reported yield increment from SRI to a greater number of PT, and more efficient resource capture and apportionment of nutrients for grain production (Nissanka and Bandara, 2004; Stoop *et al.*, 2002). Successful yield enhancement under SRI is reported only from farm plots with high nitrogen supplying ability of the soil and accumulated organic carbon from surface to deep soil, attributable to the long-term practices of extensive organic applications and deep plowing; so the high yield from these SRI farms was mainly due to high soil fertility, especially 'the great nitrogen-supplying ability of the soil, rather than "synergetic effects" (*sic*) of SRI components' (Tsujimoto *et al.*, 2009: 70). The low nitrogen and potassium levels in the soil of Basudha farm thus may account in this study for overall low grain yields.

The role of transplant density and spacing

Spacing of rice hills at 25 cm × 25 cm (up to 16 transplants m^{-2}) is considered to be most conducive for a combination of yield characteristics in the SRI plots (Stoop *et al.*, 2002; Thakur *et al.*, 2010b), and we have strictly followed this stipulated spacing on all SRI and conventional plots. Our experiments therefore cannot tell if the results are likely to change with closer spacings or greater transplant densities. Some experiments (Latif *et al.*, 2005; Menete *et al.*, 2008; Sheehy *et al.*, 2004), however, found the use of wider spacing of rice plants in SRI to have resulted in lesser yield per unit area than conventional rice farming practices. In these studies, SRI failed to achieve the desired yield enhancement plausibly because the growth of seedlings transplanted at wide spacing 'exceeded the [nutrient] capacity of those soils' (Thakur *et al.*, 2010b: 156).

The role of genotypes

Yield enhancement was observed in certain studies, even where SRI was not strictly followed (Senthilkumar *et al.*, 2008; Thakur *et al.*, 2010b). Conversely, SRI failed to elicit yield improvement in some studies (McDonald *et al.*, 2006, 2008). Both types of evidence indicate that rice yield components are flexible, responding to different field management regimes depending on the cultivar genotype. Some cultivars may not be suitable for SRI conditions (e.g. low transplant densities, limited water supply).

Most rice breeding programs employ selection criteria with respect to tillering (only three to four tillers/plant), optimum plant densities and response to chemical fertilisers, all of which differ fundamentally from what would be desirable for the SRI-adapted cultivars (Stoop *et al.*, 2002). All the yield components – tillering ability, panicle density and grain weight – depend on the cultivar genotype, albeit greatly influenced by environmental conditions and field management practices (De Datta, 1981). Extensive interactions between genotypes and environment result in adaptation of different varieties to specific environmental conditions (Xing and Zhang, 2010). For a reliable prediction of the yield response to SRI, it is necessary to identify the 'cultivars that have been proven to be optimally adapted to a particular system' (Stoop *et al.*, 2009). The cultivars used in our study were shy tillering landraces, and therefore showed no definitive change in PT in the SRI conditions. However, the grain yield components of the lowland variety Shiuli under SRI conditions showed significant improvement compared with the MST treatment, indicating its responsiveness to SST and younger seedling age at transplanting.

LIMITATIONS OF THE STUDY AND THE NEED FOR FURTHER RESEARCH

Most of the studies that have reported spectacular effects of SRI used only a few rice varieties, most of which are modern cultivars, grown in irrigated lowland conditions.

Consequently, their practical agronomic relevance to rain-fed local rice varieties in much of South Asia remains limited. Also, the evidence in literature of adverse or no effect of SRI is based on short-term, simple assessments through field experiments conducted in a single season (e.g. Sheehy *et al.*, 2004) or confined to a single rice genotype (e.g. Latif *et al.*, 2009; Senthilkumar *et al.*, 2008).

We have not used any modern rice varieties in our study because they are usually bred to optimise production under favourable soil and water conditions (Pandey and Pal, 2007; Stoop *et al.*, 2009). Instead, we have used two traditional rice landraces, which are tolerant of various local environmental stresses (such as low soil fertility). However, not all traditional varieties can outperform modern varieties in marginal environments. The yield performance of the traditional variety, Basmati, for example, is marginally better under SRI than under conventional transplanting practice, but its grain yield is considerably poorer than most hybrid rice varieties under the same management regime (Mahender Kumar *et al.*, 2010). Thus, a comparison of yield performances between modern elite varieties and local landraces under SRI conditions would be spurious. Our study has precluded this bias, and compared two low-yield traditional rice varieties that are grown on rain-fed upland and lowland farms.

Clearly, two local varieties are not adequate to find the degree of genotypic sensitivity of rice varieties to SRI conditions. However, experimental studies with local landraces are hard to come by. In view of the wide genetic diversity of rice, with thousands of extant varieties, each adapted to a specific edapho-climatic condition (Deb, 2005; Oupkaew *et al.*, 2011), it may take an indefinite period of time for researchers to ascertain the precise relationship between the genotypes grown in different environmental conditions and respective grain yield-related characteristics.

CONCLUSIONS

Rice grain yield is a quantitative trait and characterised by low heritability and a high genotype × environment (G × E) interaction (Farooq *et al.*, 2009). To determine the effect of a cultivation technique on yield, it is important to consider the cultivar genotype adapted to specific land type and local environmental conditions, including soil nutrient levels and seasons of cultivation (e.g. winter vs. summer). Therefore, the complex task of assessing the specific merits of the various rice cultivars and production systems is 'compounded further by the numerous location-specific natural and socio-economic factors that are encountered in any farming environment' (Stoop *et al.*, 2009: 1499).

Our study contradicts the inference of McDonald *et al.* (2008) that there is no *prima facie* evidence of significant yield increase from SRI in wet paddy cultivation in 'countries outside Madagaskar', as the mean yield from young transplants of Shiuli was significantly greater than conventional MST (Figure 3). However, the effect is evident only for the lowland variety Shiuli (Table 5 and Figure 2). For both rice varieties tested in our experiment, the TG and PD fluctuated with years, a likely response to the amount of rainfall, but the mean PD in both the varieties was greater in young transplants. This is in agreement with the SRI results from Mali: Although experimental land was not optimally levelled and the irrigation schedule was the same as for the non-SRI irrigation scheme, yield components significantly improved in SRI plots (Africare, 2008; Styger *et al.*, 2011). Nevertheless, the extent of yield improvement in our study is far from spectacular (Figure 3). It remains to be examined if the yield-enhancing effect of SRI in Madagascar, Mali and in our study (with Shiuli) is a result of the selection of appropriate rice cultivars, which have not been used in other experiments in other countries. Because many farmer landraces are characterised by different farmer-selected properties not related to yield components, it seems plausible that the yield of those rice genotypes (e.g. Tulsa) may not respond well to the SRI conditions, while others would.

The results of our study show that SRI tends to improve TG for Tulsa with transplant age of 10 and 14 days, and for Shiuli with transplant age of 10, 14 and 18 days, compared with SST plots with 28-day-old transplants (Table 4). For Shiuli, the only seedling age at transplanting that was associated with considerable TG enhancement was 14 days, compared with MST (Table 5 and Figure 3). Yield was also significantly greater in young Shiuli transplants than the MST (Table 5 and Figure 3). This apparent yield advantage of SRI over conventional MST disappeared in the upland rice Tulsa. Conversely, SRI was clearly a disadvantage for PT compared with the conventional MST (Table 5 and Figure 2), indicating that SRI may not be particularly economical for rain-fed upland varieties in spite of the fact that many upland varieties, including Tulsa, are moderately drought-tolerant.

The controlled water regime of alternate drying and flooding of SRI may not always improve yield in lowland varieties, as indicated by Satyanaraya *et al.* (2007). In our study, rice yield improvement in SRI plots was absent in the upland variety Tulsa. Although the yield from SRI was significantly greater compared with the conventional MST plots in the lowland variety Shiuli, the extent of improvement was restrained by water stress from scanty or delayed rains in some years. Given the fact that resource-poor farmers do not have access to irrigation in their upland farms and must rely on precipitation, SRI may not be of any practical benefit to rain-fed upland farms – unless the production system is coupled with some reliable water management system, such as stored rainwater for intermittent irrigation during periods of dry spells. It would therefore be safe to recommend SRI specifically for certain lowland rice varieties rather than a blanket prescription for any and all varieties.

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