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ORIGINAL PAPER

Opportunities for water saving with higher yield from the system of rice intensification

A. Satyanarayana · T. M. Thiyagarajan · Norman Uphoff

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Abstract The system of rice intensification (SRI) developed in Madagascar, is showing that by changing the management of rice plants, soil, water and nutrients it can increase the yields of irrigated rice by 25–50% or more while reducing water requirements by an equivalent percent. This gives farmers incentive to reduce their irrigation water use when growing rice, especially since SRI methods can also reduce farmers' costs of production which increases their net income ha^{-1} by even more than yield. Even though these results sound fantastic, the validity of SRI concepts and practices has been demonstrated in more than 20 countries to date. This article considers, first, the methods that make these improvements possible and how these are achieved. It then briefly surveys SRI experience in five Asian countries, incentives in addition to yield, water-saving and profitability for adopting SRI, and possible limitations or disadvantages with the methodology. Next, it comments on the debate over SRI in the agronomic literature and then adds to the empirical record by reporting in some detail on SRI evaluations in two of India's main rice-growing states, Andhra Pradesh and Tamil Nadu, where water availability is becoming more problematic and where SRI use is spreading. Finally, the article briefly discusses some implications of saving irrigation water by changing resource management rather than by using on more or different inputs.

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A. Satyanarayana
A.N.G.R. Agricultural University, Hyderabad, India

T. M. Thiyagarajan
Rice Research Station, Tirur, Thiruvallur, Tamil Nadu, India

N. Uphoff (✉)
Cornell International Institute for Food, Agriculture and Development, Cornell University, 31 Warren Hall, Ithaca, NY, 14853, USA
e-mail: ntu1@cornell.edu

Introduction

Scarcity of water for agricultural production is becoming a major problem in many countries, particularly the world's leading rice-producing countries, China and India, where competing and growing demands for freshwater are coming from other sectors. Also, rainfall reductions and variability create problems for farmers even if only a cyclical rather than a permanent constraint. Rainfall patterns in many areas are becoming more unreliable, with extremes of drought and flooding occurring at unexpected times. Being able to economize on water use for irrigated rice production is thus becoming more important.

Because irrigated rice production is the leading consumer of water in the agricultural sector, and rice is the world's most widely consumed staple crop, finding ways to reduce the need for water to grow irrigated rice should benefit both producers and consumers. Rice has long been believed that to be an aquatic plant, or at least a hydrophilic one. The most widely-known text on rice says that it "thrives on land that is water saturated, or even submerged, during part of all of its growth cycle... most rice varieties maintain better growth and produce higher grain yields when grown in a flooded soil than when grown in nonflooded soil" (De Datta 1981, 41, pp. 297–298). Evidence shows this view to be incorrect, however (e.g., Ramasamy et al. 1997; Lin et al. 2005). The International Water Management Institute (IWMI) has published a monograph bringing together evidence on this relationship (Guerra et al. 1998). Still, it is widely believed that rice needs or grows better in standing water.

Getting farmers to adopt water-saving methods in rice production has been impeded by the fact that, so far, there is little resulting increase in yield and profitability that would compensate farmers for their greater labor and management effort required. Small yield increases in the range of 5–10% may not suffice to justify the added cost and inconvenience. Private decision-making need not take account of externalities such as the losses to society from excessive use of water, which has opportunity costs, or of the direct costs to downstream farmers who are deprived of the water that they need for growing crops. So there need to be very attractive options to induce changes in production practices, especially age-old ones.

The system of rice intensification

At a time when rice farmers in many countries must begin finding ways to achieve their production goals with less use of water, because of growing water shortages and competing demands, an innovation in rice-farming methods has become available known as the system of rice intensification (SRI). It can (a) increase yields and production so that economic and food-security goals are met at the same time that it can (b) reduce farmers' costs of production, enhancing profitability, and (c) decrease the amounts of irrigation water required (Stoop et al. 2002; Uphoff 2003; Randriamiharisoa et al. 2006).

SRI origins

SRI was developed almost 25 years ago by Henri de Laulanié, a French Jesuit who spent more than three decades in Madagascar trying to devise better production methods that would improve the lives of rural households who were impoverished and heavily dependent on rice (Laulanié 1993). Relying as little as possible on external inputs, he sought a methodology that would be both accessible to poor and marginal farmers and environmentally-friendly. Changes introduced in the management of the rice crop, enumnerated below, elicit from any rice genome different and more productive *phenotypes*, including larger root systems (see Figs. 1, 2). That this growth and performance is achieved with substantial reductions in water application, usually 25–50%, should interest irrigation specialists and policy-makers.

Fig. 1 Individual rice plant grown under SRI conditions. This variety MTU 7029, known as Swarna, is widely grown in Andhra Pradesh and other Indian states and is normally 'shy-tillering.' With SRI methods, however, its phenotype exhibits greatly increased tillering and grain formation. Average Swarna yields have been 6.55 tons ha^{-1}, while with SRI methods they have averaged 10.2 tons ha^{-1} (picture courtesy of Dr. A. Satyanarayana)

The SRI methodology

How is 'more crop per drop' achieved? SRI changes the management of rice plants, and of the soil, water and nutrients that support them, in simple but specific ways to create optimal growing environments for rice plants so that their genetic potentials are better expressed. All plant and other phenotypes are the products of interaction between genetic endowments and environmental conditions, referred to often as 'G × E' interaction. Instead of accepting 'E' as given, and trying to raise production primarily by manipulating 'G' as has been the strategy of plant breeders, SRI seeks to improve the 'E' for any rice 'G.' SRI is not a set technology; rather it is based on certain insights about how rice plants can be induced to become more productive, particularly by (a) eliciting greater root growth, which is visible and (b) enhancing soil biotic activity, which is not.

Fig. 2 Root system of single rice plant, MTU 1071, grown with SRI methods at Maruteru Agricultural Research Station in Andhra Pradesh, India (picture courtesy of Dr. P. V. Satyanarayana, Maruteru)

The recommended methods derived from SRI concepts are always to be tested and adapted to local conditions. The age of transplanted seedlings, their spacing, and the amount and timing of water deliveries, e.g., should be evaluated and adjusted in the field for best results. The basic elements of SRI practice are the following:

1. SRI methods give highest yield when *young seedlings* are transplanted, < 15 days old and preferably only 8–12 days, i.e., before the start of the 4th phyllochron (Stoop et al. 2002). This preserves plants' potential for tillering and root growth that is compromised by later transplanting, as seen from factorial trials (Randriamiharisoa and Uphoff 2002). Transplanting is no longer considered a necessary part of SRI because its concepts and methods are being adapted for direct seeding to save labor. However, at present, transplanting is the most reliable and widely used practice with SRI.
2. Transplanting should be done *carefully* to avoid trauma to the plants' roots, and also *quickly* to avoid their becoming desiccated. Seedlings are raised in an unflooded, garden-like nursery and then transplanted within 15–30 min after uprooting. *Shallow* transplanting is recommended, only 1–2 cm deep, with roots laid in the soil as horizontally as possible. (Plunging them into the soil vertically inverts the seedlings' root-tips upward, slowing the plants' recovery from the shock of transplantation and delaying their resumption of growth.)
3. Plant density is greatly reduced with SRI compared to conventional rice cultivation. Instead of replanting seedlings in clumps of three to six plants, they are *transplanted singly* and in a *square pattern*. Initially, spacing of 25×25 cm is recommended, but as SRI practices improve the soil over time, wider spacing can later give even higher yields. Sparse planting avoids the inhibition of root growth that results from crowding; and by exposing plants to more light and air, SRI creates 'the edge effect' (also known as 'the border effect') for the whole field.
4. Seedlings are transplanted into a muddy field rather than one flooded with standing water. During the vegetative growth phase, *paddy soil is kept moist but never continuously saturated* because flooding creates hypoxic soil conditions that cause rice roots to degenerate. Under continuous flooding, up to three-fourths of roots degrade by the flowering stage (Kar et al. 1974). The SRI recommendation has been to maintain 1–3 cm of standing water on the field after panicle initiation. However, this may be more than necessary. Some SRI farmers who practice alternate wetting and drying (AWD) throughout the crop cycle, with no continuous flooding, report good results.
5. To control weeds, use of a *mechanical weeder* is recommended, starting ~10 days after transplanting, with additional weedings every 10–12 days until the canopy closes. One or two weedings is usually sufficient to control most weeds; however, additional weedings are seen to boost yield by 0.5–1.0 tons weeding^{-1}, or more. *Soil aeration* appears to stimulate the growth of aerobic bacteria and fungi and associated organisms in the soil food web. Planting in a square pattern allows farmers to weed their fields in perpendicular directions, which achieves more and better soil aeration.
6. SRI was originally developed using chemical fertilizer to augment soil nutrient supplies. But when

the Madagascar government cut subsidies in the late 1980s, SRI farmers were encouraged to apply *compost* instead. Used together with other SRI practices, this gave even better results and was preferable for cash-poor farmers. The advantages from using compost have been seen from factorial trials (Uphoff 2003), but if organic matter is not available, SRI practices can be used successfully with fertilizer.

This set of practices, even when used incompletely, usually enhances grain yield. With precision and care, yields in the range of 10–15 tons ha^{-2} or even higher have been achieved. These practices are all known to have positive effects on yield (Horie et al. 2005). What has not been well researched is the extent to which they have positive effects on soil biota, which in turn make contributions to plant growth, health and productivity, e.g., through biological N fixation; P solubilization by aerobic bacteria (Turner and Haygarth 2001); N cycling by protozoa and other mesofauna (Bonkowski 2004); mobilization of P and other nutrients by mycorrhizal fungi; microbial and fungal production of phytohormones that promote root growth; and positive effects of rhizobial endophytes (Feng et al. 2005; Dazzo and Yanni 2006). These and other processes are considered in Uphoff (2005) and Randriamiharisoa et al. (2006). Much remains to be evaluated and ascertained about the processes contributing to SRI effects, but the effects are well documented.

Water-saving possibilities associated with economic benefits

Evidence on increases in water-saving and income with SRI has been accumulating from a number of countries. Here we summarize results from independent assessments done in five of the 25+ countries where SRI has been introduced.

China

When the China National Hybrid Rice Research and Development Center began evaluating SRI methods in 2000, it found that with careful management, water applications for rice production could be reduced by as much as 65% on SRI plots compared with previous applications while still getting 1–2 tons ha^{-1} more production on top of the record-high yields that it could obtain with the its hybrid varieties (Prof. Yuan Longping, CNHRRDC director, personal communication). In 2001, an on-station record of 12.9 tons ha^{-1} was set at the center with SRI methods. That year, the center's Super-1 hybrid variety grown with SRI methods in Sichuan province gave a yield of 16 tons ha^{-1} in trials, verified by the Sichuan Provincial Department of Agriculture, 35.6% higher than the 11.8 tons ha^{-1} achieved with the same hybrid and conventional, more water-intensive methods (Yuan 2002).

An evaluation done in 2004 for China Agricultural University (CAU) on the use of SRI methods in Sichuan province documented results in Xinsheng village where the number of SRI users had gone from 7 in 2003 to 398 the next year (65% of farmers). Researchers were interested in learning why this great increase. Water reduction for farmers using SRI in the 2004 season was calculated to be 43.2%, with water costs reduced from 72.43 yuan mu^{-1} with conventional cultivation in 2002, to 39.76 yuan mu^{-1} using SRI methods in 2004 (15 mu = 1 ha) (Li et al. 2005).

The rapid switch to SRI was partly due to the robustness of SRI yield under water-stress conditions. 2003 was a drought year, when yield with conventional methods declined by one-quarter, from 6.06 tons ha^{-1} in 2002 under normal conditions, to 4.47 tons ha^{-1} with drought. Farmers who used SRI methods, however, saw their yields *go up* by 10%, to 6.60 tons ha^{-1} in 2003. The next year, a season with more typical water supply, conventional methods yielded 5.64 tons ha^{-1} while SRI produced 7.61 tons ha^{-1} (Li et al. 2005).

Another incentive for adoption was increased profitability. Gross farmer income mu^{-1}, not counting family labor which farmers do not normally consider as a cost of production, doubled with SRI methods, reaching 377.03 yuan mu^{-1} in 2004 compared with 188.81 yuan mu^{-1} using conventional methods in 2002. (Both were average rainfall years, and this comparison was calculated using constant prices.) When CAU researchers calculated net income with an imputed cost for family labor, they found that farmers' net income mu^{-1} had increased by 48% with SRI.

In both the survey of SRI users and in focus-group discussions, farmers in the village identified water-saving as a major advantage of SRI, although in both questionnaires and focus groups, farmers rated labor-saving as the greatest benefit of SRI. This was surprising since SRI has usually been regarded as a more labor-intensive method for growing rice. As discussed below, we are finding that this is not necessarily or always the case.

Cambodia

An evaluation of SRI experience commissioned in 2004 by GTZ, the German development cooperation agency, surveyed 400 SRI users and 100 non-SRI users, randomly selected in five provinces (Anthofer et al. 2004). Although not all farmers considered as 'SRI users' were using all of the recommended practices, their average yield was 41% higher than that of non-SRI users, and their economic returns ha^{-1} were 74% higher. (To avoid any 'small plot' effect, all yields from SRI plots < 0.3 ha were excluded from the analysis.)

No volumetric assessment could be made post hoc of water use by SRI farmers; however, their number flooding during transplanting fell from 96.3% before the adoption of SRI, to 2.5% after; and those 'keeping soil just moist' went from 3.5 to 92.3%. During vegetative growth, continuous flooding was reduced from 64.3 to 22.4% while alternating wetting and drying went from 35.7 to 77.6%. This indicates substantial water savings, although managing water to reduce applications was reported to be the most difficult SRI practice for these farmers to adopt, given the topography, climate and lack of control structures. According to the GTZ report, three conclusions that Cambodian farmers drew from their experience with SRI were: 'Less water [is] required,' 'Rice grows well even when the field is dry,' and 'More drought resistance.'

The NGO that introduced SRI into Cambodia (CEDAC) did its own evaluation of 120 farmers who had practiced the new methods for 3 years (2001–2003) to identify changes over time and assess SRI's sustainability (Tech 2004). This study documented a doubling of average yield (even with incomplete use of the methods, as in the GTZ study) from 1.34 to 2.75 tons ha^{-1}, while farmers' rice income ha^{-1} went from 460,700 riels before using SRI to 869,800 riels 3 years after adoption.

The volume of water used could not be measured retrospectively. However, SRI farmers' expenditure for water went from 19,100 riels ha^{-1} before SRI adoption to 9,600 riels ha^{-1} in their second and third years of SRI use. Specifically, pumping costs went from 13,700 riels ha^{-1} before SRI to 7,000 riels ha^{-1} in the third year. This indicates that water use was reduced by about half while production and income roughly doubled, so the returns to water applied quadrupled.

Indonesia

A Nippon Koei technical assistance team managing the Japanese-funded Small-Scale Irrigation Management Project in Eastern Indonesia began SRI trials with farmers on 1.6 ha in 2003. By the end of 2005, 1,849 on-farm comparison trials had been conducted on 1,363 ha. SRI yields averaged 7.23 tons ha^{-1} compared with 3.92 tons ha^{-1} using standard methods, an 84% increase (Sato 2006). Project engineers calculated water saving with SRI to be 40%, while their economic analysis showed costs of production reduced by > 25%, particularly because of lower fertilizer applications (cut by 50%). Net income calculated from Lombok data went from 1.2 million rupiahs ha^{-1} with standard methods to 6.2 million rupiahs ha^{-1} with SRI. This increase (> 400%) in part reflected how unprofitable conventional rice production has become given the high cost of purchased inputs. In the Batu Bulan dam irrigation scheme, the net return ha^{-1} on SRI plots was 7.2 times higher than from adjoining conventional plots (Sato 2006). Such results help explain why the project expects > 4,000 ha to be under SRI management in 2006.

Philippines

An evaluation of SRI done in 2003 by farmer field schools supported by the National Irrigation Administration in three communities in Negros Occidental calculated that with SRI methods they were able to reduce their water use by 67% (Lazaro et al. 2004). At the same time, their SRI yield of 7.33 tons ha^{-1} was more than double the 3.66 tons ha^{-1} produced with a 'modern' system of rice production (TQPM) that involves the use of fertilizer and more water; and it was almost triple the 2.65 tons ha^{-1} obtained with standard farmer practice. Net income ha^{-1} from SRI production was 25,054 pesos, more than double the 11,130 pesos ha^{-1} with TQPM and more than triple the 7,592 pesos ha^{-1} from farmer practice. So SRI made possible substantial reductions in the water needed for rice production in Negros Occidental while increasing farmers' returns from using less water.

Sri Lanka

Water-saving potential can be seen also from an evaluation of SRI methods carried out in this country by the IWMI in 2002. A team of IWMI researchers surveyed 60 farmer using SRI methods and 60 not using them, randomly selected in two districts. Most of the farmers classified as SRI users were not using all of the recommended practices, or using all as recommended; yet even so, there was a 44% increase in yield ha^{-1} with SRI, and more than a doubling of net income ha^{-1} compared to conventional methods (Namara et al. 2004).

The average number of paddy irrigations for SRI farmers was 24 in the dry season and 22 in the wet season, compared with 32 and 29 for non-SRI farmers, a 25% reduction (Namara et al. 2004: Table 10). Given the higher yields obtained with SRI methods, this means that water productivity in terms of the number of tons of rice produced per irrigation application was increased by 90%. SRI farmers reported investing 30% fewer hours of labor in irrigation activity. The evaluators noted that water reductions with SRI would probably have been even greater if groundwater providers had been charging farmers for water on a volumetric basis rather than simply according to the number of water issues.

These evaluations of SRI experience done for a variety of independent institutions (China Agriculture University, GTZ, IWMI, the Philippines National Irrigation Administration, and Nippon Koei) in differing environments—Cambodia, China, Indonesia, Philippines and Sri Lanka—all point to substantial water savings being accompanied by significant gains in rice production and profitability.

Other SRI incentives for using less water

SRI results reported from these and other countries indicate additional benefits from adopting the new methods that can make the use of less water in irrigated rice production more attractive.

Reduced agrochemical use

Farmers who use SRI methods widely report that their rice plants are more resistant to damage from pests and diseases, so that use of agrochemical protection becomes unnecessary or uneconomic. The reasons for this could be related to the theory of trophobiosis proposed by Chauboussou (2004), but research needs to be done to ascertain the extent and explanations of this effect, which not only lowers production costs but has benefits for soil and water quality. The effect seems to be associated with an increase in organic sources of fertilization, accompanied by a reduction in the use of synthetic fertilizer.[1]

Reduction in seed requirements

With SRI, seeding rates are greatly reduced, to 5–10 kg ha^{-1}, only 10–20% of conventional rates. Especially for poor farmers, this is a real benefit. An Indian farmer informed the Chief Minister of Andhra Pradesh that with SRI he had produced 92 bags of rice (4,600 kg) from just 2 kg of seed (*The Hindu*, November 16, 2005).

Resistance to abiotic stresses

In addition to reducing losses to pests and diseases, SRI practices produce rice plants that can better resist damage from the effects of typhoon (Sichuan, September 2002; Zhejiang, August–September 2005); cyclone (Andhra Pradesh, December 2003); cold snaps (Andhra Pradesh, February 2004); and drought (Sri Lanka, 2002–2004; also Andhra Pradesh and Cambodia in recent years). SRI plants can, of course, be damaged by extreme winds, rain, cold or desiccation; but farmers find that their SRI rice plants have observably more resilience and capacity to withstand climate-induced losses (see Fig. 3).

Less economic risk

Farmers using SRI methods are less subject to economic failures, even though SRI practices initially appear to entail greater risk (smaller, fewer plants, in drier soil). However, evaluations by IWMI and GTZ based on random samples of SRI users and non-users have found

Fig. 3 Rice fields in Dông Trù commune, Hanoi province, after typhoon in September 2005. Conventional rice-growing methods were used in field on right, while SRI methods were used in field on left, with center strip having closer plant spacing to evaluate the effect of this practice. (picture courtesy of Elske van de Fliert, FAO advisor on vegetable IPM, Hanoi)

[1] In Cambodia, where at least 40,000 farmers were using SRI methods in 2005, compared with just 28 in 2000, a survey of 120 farmers who had used SRI for three years found that compost use had gone up, on average, from 942 kg ha^{-1} to 2.1 tons ha^{-1}, with a doubling of yield, while chemical fertilizer use had fallen from 116 to 67 kg ha^{-1}, and use of chemical pesticides went from 35 to 7 kg ha^{-1}. Farmers' cost of production had declined from 231,000 riels ha^{-1} before SRI to 113,140 riels ha^{-1} with SRI (Tech 2004). GTZ's evaluation of SRI in Cambodia documented a \$23 ha^{-1} reduction in costs of production, which together with \$66 more income ha^{-1} from higher yield raised farmers' net profit ha^{-1} to \$209 ha^{-1}, compared to \$120 ha^{-1} with standard methods (Anthofer et al. 2004).

SRI methods to be less risky overall.[2] Anthofer et al. (2004: 37) concluded: "SRI is an economically attractive methodology for rice cultivation with a lower economic risk compared to other cultivation practices."

Higher milling outturn

A bonus with SRI is that—in addition to getting higher yield of paddy rice ha^{-1}—when this product is milled, there is a resulting outturn of saleable rice. SRI paddy contains fewer unfilled grains as a rule, and therefore produces less chaff; and as there is less shattering during milling, the percent of broken grains is reduced. SRI methods thus add a 'bonus' of about 15% onto the higher paddy yields obtained and will increase farmers' net income still more if millers pay the premium for SRI paddy that farmers deserve.[3]

Shortening of the crop cycle

Farmers using SRI methods have found their SRI paddy maturing 5–20 days sooner while giving higher yield. Dates of planting and harvesting are the least ambiguous agronomic data. Harvesting crops sooner reduces their exposure to storm or other damage and may permit the planting of another crop within that season. It also reduces the total amount of irrigation water needed.[4]

Possible limitations or disadvantages of SRI

Weeding

When fields are not kept continuously flooded, weed growth becomes more of a problem, and many farmers use excess water to reduce their labor requirements for weed control. Herbicide use is effective with SRI, but it does not have the positive soil-aerating effects achieved by using rotary hoes or cono-weeders. These implements while removing weeds create more favorable conditions for plant root growth and for the majority of soil biota that are aerobic. Weeding can be quite labor-demanding, but its timing is more flexible than is transplanting. Farmers are inventing or modifying tools that reduce the labor time required for weeding, even motorizing this operation, so weeding is now less of a deterrent to SRI adoption.

Labor-intensity

SRI has been considered too labor-intensive for many farmers to adopt. This was given as a reason for the disadoption of SRI by up to 40% of farmers, particularly poor farmers, surveyed in Madagascar by Moser and Barrett (2003). However, evidence is accumulating that once farmers become more comfortable and skilled with the new methods, SRI can become *labor-saving*. In the evaluation reported above from Sichuan, China, farmers ranked labor-saving as the greatest attraction of SRI, more than its water-saving, and more than its increases in yield and profitability (Li et al. 2005). In Cambodia, 55% of 120 farmers who had used SRI for 3 years evaluated the new system as 'easier' to practice, whereas only 18% considered it 'more difficult'; 27% said there was 'no difference' (Tech 2004). Anthofer et al. (2004) found no significant difference in labor requirements on average: 305 h ha^{-1} for SRI vs. 302 h ha^{-1} with conventional methods. An average for all SRI users masks variation as beginners expend more time while experienced SRI users require correspondingly less labor ha^{-1}.[5]

[2] The IWMI evaluation in Sri Lanka showed that, given SRI's higher yield and lower costs of production, rice farmers using the new methods were > 7 times less likely than conventional farmers to experience a net economic loss in any particular season (Namara et al. 2004: Table 15). The GTZ evaluation of Cambodian farmers' experience with SRI, assessing their risk of falling short of some target net income, concluded that for a \$100 ha^{-1} objective, an SRI farmer had a 17% risk of falling short, whereas it was 41% for a conventional farmer.

[3] Andhra Pradesh millers have estimated that their outturn with SRI goes up from ~67 to ~75%, justifying payments to farmers of 10% more $bushel^{-1}$ for SRI paddy. This is also reported from the Mahaweli System 'H' in Sri Lanka (U. G. Abeygunawardena, Ministry of Agriculture, personal communication) The first sugar cooperative in Cuba to take up SRI (CPA Camilo Cienfuegos, Bahia Honda) has seen its milling rate with SRI paddy go up by ~15%, from 60 to 68–71% (personal communication, July 2004). In China, the milling rate with SRI paddy has been measured to be 16.1% above that of conventionally-grown rice of the same variety, and head milled rice was 17.5% higher (Jun 2004).

[4] In 2004, farmers in Morang district, Nepal, harvested their SRI crop on average 15.1 days sooner with 114% higher yield (7.85 vs. 3.37 tons ha^{-1}); in 2005, with less favorable growing conditions, farmers planting the same variety (*Bansdhan*) reduced their time to harvest on average by 19.5 days, with 91% higher yield (5.51 vs. 2.88 tons ha^{-1}). Data provided by the Morang District Agricultural Extension Office, Biratnagar, Nepal. More rapid maturity of SRI crops has been reported also from Cambodia, China, India and Sri Lanka.

[5] An evaluation done of 108 farmers in Madagascar who were using both SRI and conventional methods documented that while first-year users required more labor ha^{-1}, by the fourth year, SRI users needed 4% less labor, and by the fifth year, 10% less (Barrett et al. 2004). Other studies have shown a faster reduction in SRI labor requirements. A study of SRI methods adapted for rainfed rice production in West Bengal, conducted by IWMI's India program, found both greater yield and net income from SRI being accompanied by an 8% reduction in labor requirements ha^{-1} (Singh and Talati 2005). A similar reduction is reported from Tamil Nadu state below.

So, although it has previously appeared that labor-intensity could be a barrier to SRI adoption, this is a transient constraint. Studies such as Dobermann (2004) and Namara et al. (2004) have regarded SRI as a fixed technology rather than as the evolving methodology that it is, being continuously modified and improved by farmer innovation. Farmers find various ways to reduce SRI's labor requirements, such as the roller-marker designed to speed up transplanting and the improved weeders devised by farmers in Andhra Pradesh. Once farmers realize that SRI can save them labor as well as water, seed and cash, it should become very widely adoptable.

Biomass limitations

One constraint identified by farmers and researchers is that there may not be as much biomass available as recommended for enriching the soil for best SRI results. However, if organic sources of nutrients are insufficient, the other SRI methods can be used beneficially with chemical fertilizer while concomitantly saving water. As farmers appreciate the benefits of organic soil fertilization and see the greater returns that are attainable with SRI, we expect that they will begin making better use of whatever biomass sources are available and will harvest and even begin cultivating biomass on 'non-arable' areas to increase biomass supply.

Little research and experimentation have been done on how to maximize/optimize biomass production to enhance greater soil fertility with low opportunity cost. Available tools, implements and transportation equipment are not well-suited for large-scale production and handling of biomass, so considerable efficiency gains could be made. The relative cheapness of (often subsidized) inorganic fertilization has made organic alternatives unattractive, but these price differentials are unlikely to continue in the future, encouraging research and innovation.

Water control

This is the main objective constraint on SRI adoption, since its benefits depend particularly on maintaining aerobic soil conditions, with the application of smaller but regular amounts of water to the rice field. In their first few weeks, tiny transplanted seedlings are vulnerable to inundation. This limits their use in monsoon climates where little effort has been made to provide drainage, as farmers and engineers have (incorrectly) thought it desirable to maintain flooded fields for better rice crops. Investments in drainage facilities, agronomic innovations like raised beds, and better organization among farmers to manage excess water will become more profitable with SRI, so they are likely to increase. While water control is important for success with SRI, most of the other methods—wider spacing, more organic nutrients, with reduced water application after flooding subsides—can be beneficial even without such control.

To the extent that the above disincentives/constraints can be effectively addressed, the benefits noted above should give farmers strong incentives to change their production practices for irrigated rice. Adopting SRI or some version of it can reduce water requirements by as much as 25–50% with greater production. For such savings to scale up to system level, however, all farmers in a command area would need to change their practices, so this represents a next-stage challenge. In India and Indonesia, benefits from SRI are well-enough established that irrigation departments are beginning to promote it within whole command areas to achieve such savings.

Critiques of SRI and empirical evaluations

SRI remains somewhat controversial as some rice scientists have disputed the reports and claims regarding SRI (Surridge 2004). Most critiques of SRI (e.g., Dobermann 2004; Sheehy et al. 2004; Sinclair 2004; Sinclair and Cassman 2004; McDonald et al. 2006) have not been based on the authors' direct work with SRI methods in the field and with farmers. The three small trials in China reported by Sheehy et al. (2004), for example, did not follow any protocol that SRI proponents would regard as a valid test of the methods; e.g., there was no active soil aeration, and so much N fertilizer was applied (180–240 kg ha^{-1}) that some of the SRI trials lodged, which almost never occurs when SRI is practiced as recommended (Fig. 3). For an assessment of these critiques, see Stoop and Kassam (2005).

The conclusion of Sheehy et al. (2004) dismissing SRI as having "no major role in improving rice production generally" was based on a single set of contestable trials and on crop modeling that used data from rice plants having very different phenotypes from those with SRI. More important, it is contradicted by > 5 years of research by rice scientists at major Chinese institutions, including the China National Rice Research Institute (Zhu et al. 2002, 2004; Tao et al. 2002; Lin et al. 2005), the China National Hybrid Rice Research and Development Center (Wang and Peng 2003), Nanjing Agricultural University (Wang et al.

2002), and the Sichuan Academy of Agricultural Sciences (Zheng et al. 2004).[6]

These researchers have demonstrated that SRI methods offer new opportunities for improving rice production with reduced use of water, which is becoming a major issue in China. Their research has repeatedly documented phenotypic differences between rice plants of the same variety grown under SRI conditions versus plants raised with conventional practices (including continuous flooding). In September 2004, the Chinese Ministry of Agriculture put SRI on a short list of technologies to be promoted in the major rice-growing regions of China in its effort to restore growth to that country's rice sector, which has been stagnant since 1998.

For the same reason, the Indonesian Agency for Agricultural Research and Development already in 2002 included SRI practices in its integrated crop and resource management (ICM) strategy to restore momentum to its rice sector (Gani et al. 2002). In 2004, the Indian Council for Agricultural Research began supporting SRI demonstrations in all rice-growing parts of that country after reviewing SRI results such as reported below (Subbiah et al. 2006; see also review of reports to 2005 IWMI-India conference: http://www.cgnet.in/A/A3). The central Ministry of Agriculture has advised Indian rice farmers to use SRI practices "wherever feasible" (press release, May 31, 2005). Thus, researchers and policy-makers in the world's three largest rice-producing countries are satisfied that SRI can play an important role in improving rice production, not least because of its water-saving possibilities. Positive results are also reported from other countries (see reports in Uphoff et al. 2002).[7]

SRI results in Andhra Pradesh, India

The agricultural sector in the state of Andhra Pradesh (AP) has been affected by ongoing water crises in recent years. Recurrent monsoon failures have been worsened by inter-state disputes over river-water allocations so that crises have political as well as agronomic and economic repercussions. Farmers in the state who depend on irrigation feel insecure, especially as their costs of production keep rising. Production from the state's 4 million ha of cropped area devoted to rice, about 60% of which is irrigated, had previously reached 9 million tons. In 2002–2003, however, production was only 7.57 million tons, the lowest level in 10 years, due mostly to water shortages, as well as diminishing returns from agrochemical inputs. This created a situation where SRI was attractive.

The first author, at the time Director of Extension for AP, visited Sri Lanka in early 2003 to learn about SRI directly from Sri Lankan farmers who were using the new methods. He then established 200 on-farm trials in the 2003 kharif (summer) season, 150 of them supervised by the State's extension service and 50 by the AP state agricultural university (ANGRAU). Trials were spread across all 22 districts of the state to assess the effects of SRI methods with all kinds of soils and irrigation methods. Nineteen varieties were used, and the trial areas were each 0.4 ha: 0.2 ha under SRI and 0.2 ha under the farmer's present practice. The data reported in this section were thus controlled for farmer and soil differences. Farmers' practices included mostly modern methods recommended by the State Agricultural University for irrigated rice since their resulting conventional yields were two-thirds higher than the average rice yield in AP, 3.87 tons ha^{-1}.

Results from the first season trials are shown graphically for districts in the coastal area (Fig. 4), central Telangana area (Fig. 5), and the dryer interior Rayalseema area (Fig. 6). The average regional increases in yield achieved with SRI methods and reduced water use are given then in Table 1. SRI yield advantages were consistent, although they varied by region, reflecting differences in soil characteristics and water management capacity. Results from trials conducted concurrently by the Department of Agriculture in 16 districts are shown in Fig. 7. The Department's evaluations showed SRI results to be 70% higher as their average yield was 8.34 tons ha^{-1} compared to 4.89 tons ha^{-1} from control plots.

The intra-state differences shown in Table 1 have interesting implications for improving our understanding of irrigated rice production. The more saturated soils of the low-lying coastal districts have generally been considered to offer more favorable conditions for growing rice. However, the drier upland Rayalseema districts gave the best response to SRI methods. In the intermediate Telengana region, the average yield advantage with SRI was 2.5 tons ha^{-1}, but the average increase in coastal areas was only 1.15 tons ha^{-1}, whereas in Rayalseema, it was 4.73 tons ha^{-1}. Possibly the better-drained soils in the interior harbor populations of aerobic soil biota that

[6] This research is summarized in a forthcoming book published by the China National Rice Research Institute (Zhu et al. 2006).

[7] In Bangladesh, 2 years of on-farm evaluations ($N = 1{,}093$) supervised by two NGOs (BRAC and SAFE), the Bangladesh Rice Research Institute, and Syngenta Bangladesh Ltd., with funding from the IRRI program there, likewise showed SRI benefits. Five of the six sets of trials showed increases in yield of 6–50% and in net farmer income of 4–82% (Husain 2004). Reductions in water use were reported from most of the trials, although the studies did not measure amounts. The only negative results (Latif et al. 2005) were based on < 2% of the on-farm trials.

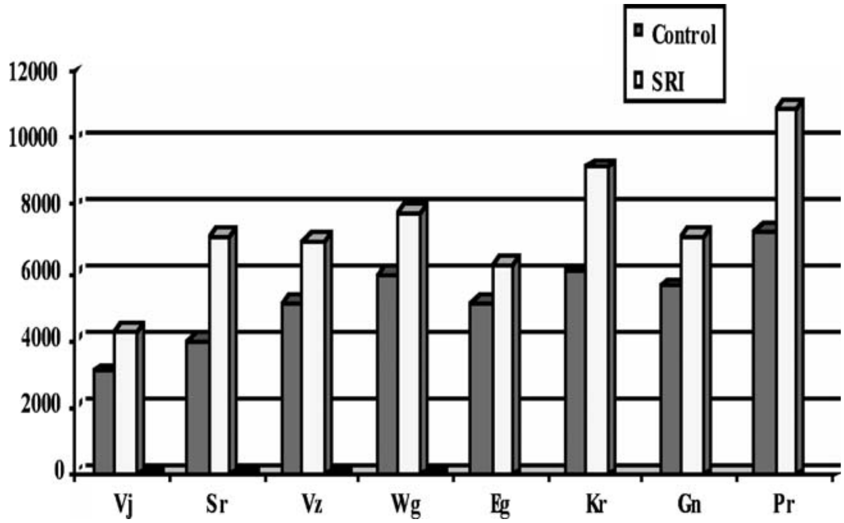

Fig. 4 Paddy yields in on-farm comparison trials of SRI versus control methods, supervised by ANGRAU research staff in the coastal region of Andhra Pradesh, by district, kharif season, 2003. Districts in coastal region: *Vj* Vizianagaram, *Sr* Srikakulam, *Vz* Visakhapatnam, *Wg* West Godavari, *Eg* East Godavari, *Kr* Krishna, *Gn* Guntur, *Pr* Prakasam

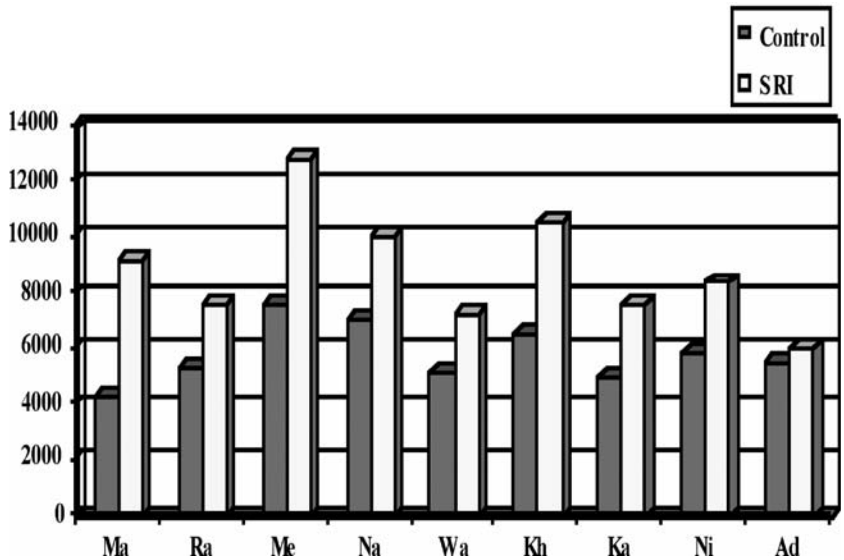

Fig. 5 Paddy yields in on-farm comparison trials of SRI versus control methods, supervised by ANGRAU research staff in Telangana region, by district, kharif season, 2003. Districts in Telangana region: *Ma* Mahabubnagar, *Ra* Rangareddy, *Me* Medak, *Na* Nalgonda, *Wa* Warangal, *Kh* Khannam, *Ka* Karimnagar, *Ni* Nizamabad, *Ad* Adilabad

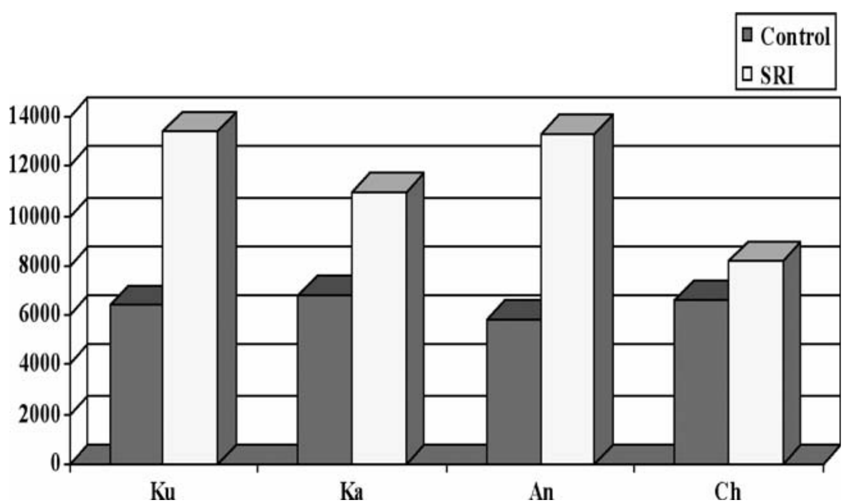

Fig. 6 Paddy yields in on-farm comparison trials of SRI versus control methods, supervised by ANGRAU research staff in Rayalseema region, by district, kharif season, 2003. Districts in Rayalseema region: *Ku* Kurnool, *Ka* Kadapa, *An* Anantapur, *Ch* Chittoor

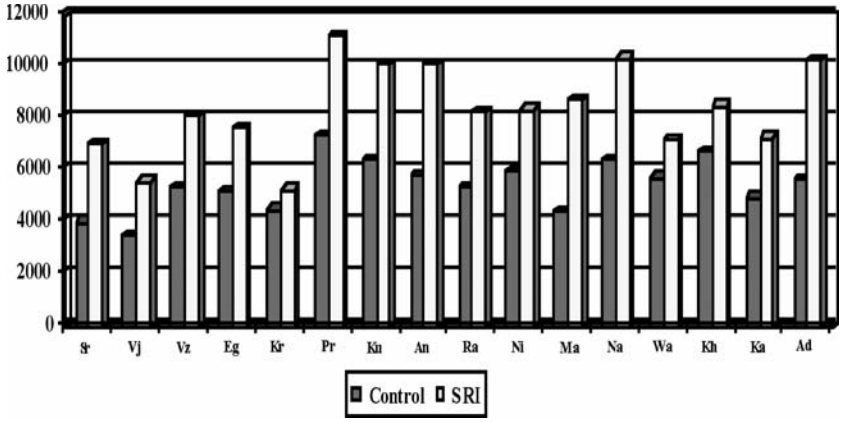

Fig. 7 Paddy yields in on-farm comparison trials of SRI versus control methods, supervised by MOA extension staff across Andhra Pradesh, by district, kharif season, 2003. Districts: *Sr* Srikakulam, *Vj* Vizianagaram, *Vz* Visakhapatnam, *Eg* East Godavari, *Kr* Krishna, *Pr* Prakasam, *Ku* Kurnool, *An* Anantapur, *Ra* Rangareddy, *Ni* Nizamabad, *Ma* Mahabubnagar, *Na* Nalgonda, *Wa* Warangal, *Kh* Khannam, *Ka* Karimnagar, *Ad* Adilabad

Table 1 Summary of results of on-farm comparison trials, supervised by ANGRAU extension staff, by region, kharif season, 2003

Region	Comparison trials (no.)	Farmer practice ave. yield (tons ha^{-1})	SRI practice ave. yield (tons ha^{-1})	SRI trial yields > 10 tons ha^{-1} (no.)	Range of SRI yields (tons ha^{-1})	Ave. SRI yield advantage (tons ha^{-1})
Coastal	84	6.54	7.69	17 (20%)	3.2–14.3	1.15
Telangana	40	6.31	8.82	10 (25%)	4.2–16.2	2.50
Rayalseema	10	6.50	11.23	6 (60%)	7.8–15.5	4.73

respond more beneficially to SRI management. These results suggest that heavy, moist clay soils, now regarded as the best for rice production, may not give best results with a change in management, as well-drained soils can produce more rice with less water provided it is reliable.

Such results from the kharif season encouraged larger numbers of farmer in rabi (winter) season 2003–2004 to use SRI methods in Andhra Pradesh. The university and extension service oversaw > 2,000 on-farm trials, but many more farmers did their own evaluations. No complete data collection was possible from all the trials. We report here results only where extension staff supervised the operations and measurement. For 94 comparisons where the farms and farmers were the same, the average SRI yield, using less water, was 9.67 tons ha^{-1} versus an average yield of 7.13 tons ha^{-1} from farmers' current practices. This average yield increase of 2.55 tons ha^{-1} was a 37.5% increase over already high yield levels as these were some of AP's best farmers.

Through 2005, 1,525 comparison trials had been evaluated by the AP extension service. The cumulative average yield advantage with SRI was 2.42 tons ha^{-1} (8.73 tons ha^{-1} vs. 6.31 tons ha^{-1} from control plots), an increase of 33.8%. Average plot size was 0.4 ha, with a range of 0.1–1.6 ha. In 2003–2004, one commercial farmer (NVRK Raju in Kurelagudem, West Godavari district) cultivated a contiguous area of 40 ha with SRI methods using five different varieties. His average SRI yield, harvested not sampled, measured by Department of Extension staff, and adjusted for grain moisture, was 11.13 tons ha^{-1}. This shows that SRI methods need not be limited to small plots.

As a standard of comparison, the average increase in yield reported from a series of site-specific nutrient management (SSNM) trials conducted across six Asian countries is only 360 kg ha^{-1} more than farmer practice (Dobermann et al. 2002). This increase was 15% as much as that achieved with SRI methods in Andhra Pradesh involving lower cost and less water requirement.

Unfortunately, there were no facilities installed on farmers' fields to measure precisely their water use, so no exact figures on water saving can be given here. However, all farmers reported using less water with SRI than with conventional practice, and the range of reductions estimated by farmers was 40–50%. Even savings half this large would be important. Field-level water savings demonstrated thus far only show the *potential* of SRI to reduce water use in irrigated rice production, however. Full water-saving benefits can only be actualized when there is widespread adoption.

With such results, interest in SRI is growing rapidly among both farmers and researchers. SRI use in Andhra Pradesh in 2005 was > 20,000 farmers, up from just 300 in 2003. One of the main incentives that farmers cite for taking up the new system is its water-saving potential. Water shortages have become a fact of life for AP farmers, threatening the continuation of their livelihoods and way of life. In rabi season 2004, the World Wide Fund for Nature (WWF) supported an evaluation of SRI with on-farm comparison trials supervised by ANGRAU with 186 farmers across 11 districts. WWF wanted to verify whether SRI methods could increase water productivity in irrigated rice production because this competes with natural ecosystems for water.

While not all farmers used the recommended SRI practices fully, the average SRI yield advantage was 22% (excluding two yields of 17 and 19.7 tons ha^{-1} as outliers). Given the reduction in water used, calculated water productivity with SRI went up from 0.57 kg rice m^{-3} of water to 2.05 kg m^{-3} of water. This implies that 72% less irrigation water could be used to produce rice (Murty et al. 2006). Substantial environmental benefits are thus possible in addition to the significant economic gains for farmers and consumers.

SRI results in Tamil Nadu, India

Rice occupies 70% of the total irrigated area in the state of Tamil Nadu (TN) and is grown on 2 million ha in different seasons throughout the year, depending upon water availability. This availability is declining, with a projected gap in water supply versus demand for irrigated crops of about 21 billion m^{-3} by 2025 (Palanisamy and Paramasivam 2000). Water shortage has already resulted in some reduction of the irrigated rice area in TN with a shift toward less water-demanding crops. During the past two decades, net area sown for rice has declined at an average rate of 84,600 ha year^{-1}. An offsetting increase in productivity of 82 kg ha^{-1} year^{-1} has made up about one-third of the impact on rice production from declining area (Thiyagarajan et al. 2000).

The recommended water application for irrigated rice cultivation is 5 cm depth 1 day after disappearance of flooded water. However, many farmers are unable to follow this recommended practice due to difficulties in controlling water flow and uncertain water availability, so they take even more whenever possible. Consecutive failure of the monsoon rains during the past 3 years has affected rice production severely through reduced water availability in rivers, tanks and ground water. Given the confluence of (a) water scarcity, (b) declining area under rice, and (c) continuing increase in population, raising rice productivity has become a serious concern to the government and rice scientists.

The advent of SRI is thus timely in Tamil Nadu. Its evaluation by the Crop and Soil Management Center of the Tamil Nadu Agricultural University (TNAU) at Coimbatore started in 2000 with field experiments at the wetland farm of TNAU assessing different methods of crop establishment, spacing, and water management. Initial trials did not show any advantage from SRI methods as grain yields were lower with plant density of 16 m^{-2} or less. The trials did show, however, that normal yields could be obtained with plant density of ≥ 32 m^{-2} without flooding the field. Evaluation was carried forward given the interest in any water-saving possibilities.

During the next two seasons, on-station experiments were conducted with two different varieties in the same location under controlled conditions as part of a project on water-saving for rice funded by the Dutch Ministry of Agriculture. Various components of SRI were assessed with replicated trials, using a Parshall flume to measure irrigation water use, also monitoring rainfall during the growing season. The plant density used for all treatments was 25 m^{-2} with square planting that permitted the criss-cross (perpendicular) use of a rotary weeder. Since the most common plant density in Tamil Nadu is 50 m^{-2} for medium-duration (125–135 days) varieties and 66 m^{-2} for short-duration (105–115 days) rice, this represented a 50–62% reduction in density.

Overall yield increases were realized from the combined effects of these management practices, with the highest yield obtained from the SRI practices (7.61 tons ha^{-1}). Mean grain yield for all water-saving treatments (6.35 tons ha^{-1}) was on par with conventional practice (6.46 tons ha^{-1}), indicating that use of younger seedlings and soil-aerating weeding had a beneficial effect. Of particular interest was the finding that in-situ incorporation of weeds into the soil with the rotating hoe, part of SRI practice, significantly increased yield (6.74 tons ha^{-1}) compared to conventional weeding (6.08 tons ha^{-1}). How much of this effect was due to the return of nutrients to the soil, and how much to soil aeration, could not be determined, however.

The productivity of water used in rice production was found to be 50–82% higher with SRI water control (0.61–0.73 kg m^{-3}) compared to conventional irrigation (0.40 kg m^{-3}) (Table 2). Conventional water management (flooding) with conventional crop establishment gave the lowest yield (6.13 tons ha^{-1}), although SRI water management with young seedlings was not much higher in these initial trials (6.29 tons ha^{-1}). SRI methods did not show consistent advantages in initial trials, although mechanical weeding had a definite positive impact on yield.

In the next season using rice variety ADTRH 1, water productivity (grain yield per unit of total water used, considering both irrigation and rainfall) varied in

Table 2 Water productivity for conventional and SRI planting under conventional and limited irrigation during wet season (September 2001–January 2002) and dry season (January–June 2002), TNAU, Coimbatore, India

	Conventional planting		Modified SRI planting	
	Conventional irrigation	Modified SRI irrigation	Conventional irrigation	Modified SRI irrigation
Wet season				
Total number of irrigations	14	9	16	11
Total water irrigated ($m^3\,ha^{-1}$)	11,853	5,205	13,347	6,699
Cumulative rainfall during the crop period ($m^3\,ha^{-1}$)	3,560	3,560	3,560	3,560
Total water used ($m^3\,ha^{-1}$)	15,143	8,765	16,907	10,259
Yield (tons ha^{-1})	6.13	6.41	6.80	6.29
Water productivity (kg m^{-3})	0.40	0.73	0.40	0.61
Dry season				
Total number of irrigations	21	15	25	18
Total water irrigated ($m^3\,ha^{-1}$)	13,406	6,213	16,634	8,419
Cumulative rainfall during the crop period ($m^3\,ha^{-1}$)	560	560	560	560
Total water used ($m^3\,ha^{-1}$)	13,966	6,773	17,194	8,979
Yield (tons ha^{-1})	6.21	5.90	6.78	6.44
Water productivity (kg m^{-3})	0.44	0.87	0.39	0.72

the wet season between 0.349 and 0.788 kg m^{-3} and in the dry season between 0.384 and 0.898 kg m^{-3} for different crop establishment and water-control practices. These water productivity levels are in line with data for India presented by Bouman and Tuong (2001), indicating productivity levels from 0.2 to 0.4 kg m^{-3}. The highest water productivity was obtained from using conventional seedlings and limited irrigation in both crop seasons, with water productivity increasing by 46 and 49% in the wet and dry seasons, respectively, compared to conventional flooded irrigation. With young seedlings, water productivity increased by 36 and 45% in the wet and dry seasons, respectively, compared to transplanting 24 day old seedlings (Thiyagarajan et al. 2005).

Further experiments were conducted in rabi season November 2003–February 2004 with split-plot design and cultivar ADT 43 (110 day duration) at the TNAU Agricultural College and Research Institute, Killikulam (8°46′N; 77°42′E; 40 m above MSL).[8] The main plot compared two methods of cultivation (SRI vs. conventional), while sub-plots assessed different nitrogen management practices. Data were collected on crop growth parameters, and on SPAD value, chlorophyll content (at panicle initiation stage), lodging ratio, and grain yield. The grain yields achieved for the whole experiment were relatively low because of an initial setback to the entire crop due to pest damage. However, despite this, the SRI methods of cultivation gave a 28% increase in grain yield, with SRI yield improvements observed under all N management practices. Of most scientific interest were the systematic changes in phenotype characteristics of the rice plants grown with SRI methods versus those conventionally grown (Table 3).

SRI has now become a prime extension focus for the Department of Agriculture which is promoting it throughout the state. SRI is being recommended for rice production areas in one of the World Bank-supported projects seeking to increase the efficiency of water use in agriculture. TNAU's experimental evaluations have showed increased yield with decreased water use as well as labor saving in weeding operations and a lower seed rate. The State government accepted a proposal to promote this modified method of rice cultivation in Tamil Nadu beginning in 2003, sanctioning US$50,000 to evaluate SRI in two major rice-growing areas.

One of these areas was the Tamiraparani River basin in southern TN, where 100 adaptive research trials (ARTs) were laid out in farmers' fields in different parts of the basin for the wet season, October 2003–March 2004. Farmers were exposed to SRI through field demonstrations and were given theoretical explanations so they understood the purpose of the modifications in practice. The trials compared SRI with conventional cultivation on areas of 1,000 m^2 each, two

[8] Pertinent agronomic information: sandy clay loam soil; pH 8.2; EC 0.35 dSm^{-1}; organic carbon 8.7 g kg^{-1}; CEC 37.5 c mol (p+) kg^{-1}; mineralization N 160 kg ha^{-1}; Olsen P 15.5 kg ha^{-1}; NH4OAcK 220 kg ha^{-1}.

Table 3 Plant characteristics and grain yield (mean values) under conventional and SRI methods of cultivation, rabi 2003–2004

Parameters	Conventional methods	SRI methods	LSD (5%)	SRI change (%)
Root length (cm)	13.2	15.6	1.7	+18.2
Root volume (m^3 ha^{-1})	10.8	12.9	0.7	+19.4
Tiller density (m^{-2})	458	477	7.3	+4.1
SPAD value[a]	33.9	36.1	1.14	+6.5
Chlorophyll a (mg g^{-1})	1.72	2.41	0.06	+40.1
Chlorophyll b (mg g^{-1})	1.00	1.07	0.01	+7.0
No. of panicles m^{-2}	437	453	5	+3.7
No. of grains m^{-2}	117	148	26	+26.5
Lodging ratio (%)	48.5	42.7	1.6	−12.0
Grain yield (tons ha^{-1})	3.04	3.89	515	+28.1
Fertilizer partial factor productivity [kg (kg N)$^{-1}$]	39.5	50.8	–	+28.6
Agronomic efficiency	10.1	15.3	–	+51.5
Physiological efficiency	32.5	41.1	–	+26.5
Recovery efficiency	30.3	37.6	–	+24.1

[a] Measure of chlorophyll content

on each farm, without replication. As in the Andhra Pradesh trials, this minimized inter-farmer and inter-farm differences for the sake of comparison.

The recommended SRI practices were:

1. 14–15 day old seedlings from simple nursery beds,
2. Planting of single seedlings per hill spaced at 20 × 20 cm; this facilitates the
3. Use of rotary weeder at 10 day intervals, up to 40–45 days after planting, and
4. Until panicle initiation (PI), irrigating to 2.5 cm depth only after small cracks developed on the soil's surface; after PI, irrigation was given after ponded water had disappeared.

Seedbed preparation and planting were done under the supervision of TNAU research staff. Rotary weeders were supplied to the farmers, and the trials were continuously monitored.

The utilization of SRI components varied according to local constraints, so not all of the new practices were applied as recommended. Only 36 farmers managed all of the components as expected, with the rest (64) missing one or more of the components. However, all farmers used 14 day seedlings (conventional practice is around 25 days) and adopted 20 × 20 cm spacing (conventional spacing is 20 × 10 or 15 × 10 cm). Ten different varieties were used.

Grain yields were recorded carefully by collecting all the panicles from five randomly selected 1 m^{-2} areas from both the SRI and conventional plots and by recording grain weight after threshing and cleaning. The yields, reported at 14% moisture, ranged from 4.21 to 10.66 tons ha^{-1} for SRI, and from 3.89 to 8.73 tons ha^{-1} for conventional cultivation (Table 4). The respective average grain yields of 7.23 and 5.66 tons ha^{-1} showed an overall yield advantage for SRI, even with incomplete utilization, of 1.57 tons ha^{-1} (27.8%).

Thirty-one farmers recorded grain yields of more than 8 tons ha^{-1} on their SRI lots, while only three conventional plots surpassed this target. The maximum yield advantage recorded for SRI was 4.04 tons ha^{-1}, a 70% increase. Yield increase was due to increased numbers of panicles m^{-2} and increased numbers of grains panicle^{-1}. Of the ten varieties used by farmers,

Table 4 Comparison of yield, labor requirement, costs of cultivation, and net returns from conventional and SRI in farmers' fields, Tamiraparani basin, 2003–2004 ($N = 100$)

	Conventional cultivation		SRI cultivation		% Difference	
	Low	High	Low	High	Low	High
Grain yield (tons ha^{-1})	3.89	8.73	4.21	10.66	+8.4	+22.1
Average grain yield (ton ha^{-1})	5.66		7.23		+27.8	
Male labor requirement ha^{-1}	50		83		+66.0	
Female labor requirement ha^{-1}	222		167		−24.8	
Total labor requirement ha^{-1}	272		250		−8.1	
Costs of cultivation ha^{-1}	21,424		19,060		−10.0	
Net economic return (Rs ha^{-1})	11,149		23,868		+114.1	

three were found to perform very well under SRI. One of these had been previously regarded as 'shy tillering,' but under SRI, it produced many more tillers, like MTU 7029 variety in Andhra Pradesh (Fig. 1).

As seen from the bottom line of Table 4, with SRI methods there was a doubling of farmers' net returns ha^{-1} with an 8% reduction in overall labor requirements. Men took over weeding operations, because these are 'mechanical' with SRI. This reduced the time that women had to devote to rice production, which was also reduced by their needing less time for transplanting. Usually SRI methods have been thought to *add* to farmers' total labor requirement. The lower labor requirement together with higher yield means that SRI increased labor productivity (rice kg day^{-1}) by almost 40%. The 40–50% reduction in water use reported means that water productivity (kg rice m^{-3} water) was raised by > 130%.

The benefits reported by TN farmers from using SRI practices, similar to those reported by AP farmers, were the following:

1. Drastic reduction in seed rate, from 60–75 to 7.5 kg ha^{-1}.
2. No need to use herbicides.
3. Multiple advantages from using rotary weeders: better weed control, less time required for weeding, incorporation of top-dressed fertilizer, aeration of the soil, incorporation of weeds and their nutrients back into the soil, and increased tillering.
4. Water savings of 40–50%.
5. Increased number of panicles m^{-2}, grains $panicle^{-1}$, grain yield, and straw yield.
6. Higher net profits for farmers.

Planting in a square pattern was the only difficulty that farmers singled out, noting that their traditional method of random planting is quicker, but it gives less yield.

The results of SRI evaluations conducted through this large set of ARTs paved the way for getting support from extension staff and leadership of the state's Department of Agriculture. Demonstration trials have now been laid out in all rice areas of the state, which should speed the adoption of SRI by still more farmers. From conversations with farmers, one of the reasons making them more receptive to SRI is the opportunity that they see now to reduce their water requirements. Not only will SRI reduce labor and costs, but it can also lessen conflict with neighbors when water is scarce. This matter of reducing conflict over water weighs heavily in the thinking of political leaders as well as farmers, in Andhra Pradesh as well as Tamil Nadu.

Discussion

Because SRI is still a new methodology, developed purely inductively, further improvements will quite probably be made as its theoretical and empirical foundations are strengthened. SRI is an unusual agricultural innovation in that its results are often better on farmers' fields than those that researchers obtain on-station. This observation has directed our attention to consideration of factors of soil biology. These can be highly variable, and it can be adversely affected by sustained applications of chemical fertilizer and agrochemical biocides. There is considerable published evidence to support this proposition (cited in Chaboussou 2004), but until more systematic research has been conducted on this question, it must remain a hypothesis.

The data presented from Andhra Pradesh and Tamil Nadu states confirm observations and results reported from other countries, that SRI offers multiple advantages and raises factor productivity, not just for water and for land, but across the full range of production inputs. That these benefits can be accomplished with less use of water is counterintuitive, given that rice has been considered to be hydrophilic if not necessarily aquatic. However, maintaining aerobic soil conditions benefits both plant roots and soil biota. The latter mobilize soil nutrients for plants and provide other services, starting with N-fixation and P solubilization by bacteria and nutrient and water access through mycorrhizal fungi. Such processes which could be producing SRI effects are discussed in Doebbelaere et al. (2003) and Randriamiharisoa et al. (2006).

An understanding of soil ecology reinforces the idea that water applications for irrigated rice production should be optimized, not maximized. While rice plants have need for water, their roots need also oxygen, as do the aerobic microbes (rhizobia, mycorrhizal fungi, etc.) and other soil flora and fauna that are beneficial for rice plants' nutrition and health (Yanni et al. 2001; Martin et al. 2001). The achievement of more yield with less water must, of course, have demonstrable scientific explanations. There is, however, already enough understanding and repetition of these results that practitioners can begin to utilize these practices while scientists from multiple disciplines work to establish more complete and rigorous explanations for them.

References

Anthofer J et al (2004) Evaluation of the system of rice intensification (SRI) in Cambodia, February–April 2004. Report to GTZ, Phnom Penh

Barrett CB, Moser CM, McHugh OV, Barison J (2004) Better technology, better plots, or better farmers? Identifying changes in productivity and risk among Malagasy rice farmers. Am J Agric Econ 86:869–888
Bonkowski M (2004) Protozoa and plant growth: the microbial loop in soil revisited. New Phytol 162:616–631
Bouman BAM, Tuong TP (2001) Field water management to save and increase its productivity in irrigated lowland rice. Agric Water Manage 49:11–30
Chaboussou F (2004) Healthy crops: a new agricultural revolution. Jon Anderson, Charnley
Dazzo FB, Yanni YG (2006) The natural rhizobium–cereal crop association as an example of plant–bacteria interaction. In: Uphoff N et al (eds) Biological approaches to sustainable soil systems. CRC Press, Boca Raton, pp 109–127
De Datta SK (1981) Principles and practices of rice production. Wiley, New York
Dobermann A (2004) A critical assessment of the system of rice intensification (SRI). Agric Syst 79:261–281
Dobermann A et al (2002) Site-specific nutrient management for intensive rice cropping systems in Asia. Field Crops Res 74:37–66
Doebbelaere S, Vanderleyden J, Okon Y (2003) Plant growth-promoting effects of diazotrophs in the rhizosphere. Crit Rev Plant Sci 22:107–149
Feng C, Shen S-H, Cheng H-P, Yanni YG, Dazzo FB (2005) Ascending migration of endophytic rhizobia, from roots to leaves, inside rice plants and assessment of benefits to rice growth physiology. Appl Environ Microbiol 71:7272–7278
Gani A et al (2002) The system of rice intensification in Indonesia. In: Uphoff N et al (eds) Assessment of the system of rice intensification: proceedings of an international conference, Sanya, April 1–4, 2000. Cornell International Institute for Food, Agriculture and Development, Ithaca, pp 58–63
Guerra LC, Bhuiyan SI, Thuong TP, Barker R (1998) Producing more rice with less water in irrigated systems. SWIM Paper 5, International Water Management Institute, Colombo
Horie T, Shiraiwa T, Homma K, Katsura K, Maeda S, Yoshida H (2005) Can yields of lowland rice resume the increases that they showed in the 1980s? Plant Prod Sci 8:257–272
Husain AMM (2004) Evaluation of system of rice intensification (SRI) trials in Bangladesh: results from IRRI PETRRA subprojects. Paper presented at World Rice Research Conference, Tsukuba, November 7
Jun M (2004) Results of research on SRI at Sichuan Agricultural University. Paper presented at 10th National conference on theory and practice for high-quality, high-yielding rice in China, Haerbin, August 26
Kar S, Varade SB, Subramanyam TK, Ghildyal BP (1974) Nature and growth pattern of rice root system under submerged and unsaturated conditions. Il Riso 23:173–179
Latif MA, Islam MR, Ali MY, Saleque MA (2005) Validation of the system of rice intensification (SRI) in Bangladesh. Field Crops Res 93:281–292
Laulanié H (1993) Le système de riziculture intensive malgache. Tropicultura 11:110–114
Lazaro RC et al (2004) Water-saving high-yielding TQPM and SRI trial runs and demonstrations in the Magballo-Balicotoc-Canlamay Integrated Irrigation Sub-Project. Report from the Southern Philippines Irrigation Support Project to the National Irrigation Administration, Quezon City
Li X, Xu X, Li H (2005) A socio-economic assessment of the system of rice intensification (SRI): a case study from Xiushang village, Jianyang county, Sichuan province. Report for the Center for Integrated Agricultural Development, China Agricultural University, Beijing
Lin X-Q, Zhou W-J, Zhu D-F, Zhang Y-B (2005) Effect of SWD irrigation on photosynthesis and grain yield of rice (*Oryza sativa* L.). Field Crops Res (in press)
Martin FM, Perotto S, Bonfante P (2001) Mycorrhizal fungi: a fungal community at the interface between soil and roots. In: Pinton R, Varanini Z, Nannipieri P (eds) The Rhizosphere: biochemistry and organic substances at the soil–plant interface. Marcel Dekker, New York, pp 263–296
McDonald AJ, Hobbs PR, Riha SJ (2006) Does the system of rice intensification outperform conventional best management? A synopsis of the empirical record. Field Crops Res 96:31–36
Moser CM, Barrett CB (2003) The disappointing adoption dynamics of a yield-increasing, low-external-input technology: the case of SRI in Madagascar. Agric Syst 76:1085–1100
Murty MVR, Gujja B, Satyanarayana A, Rao P, Riddell P, Goud V (2006) The dialogue on water, food and the environment: transforming irrigated rice cultivation for future food needs—the results of SRI trials in Andhra Pradesh. Paper for international dialogue on rice and water: exploring options for food security and sustainable environments, IRRI, Los Baños, March 7–8
Namara RE, Weligamage P, Barker R (2004) Prospects for adopting system of rice intensification in Sri Lanka: a socio-economic assessment. Research Report 75, International Water Management Institute, Colombo
Palanisamy K, Paramasivam P (2000) Water scenario in Tamil Nadu—present and future. In: Kannaiyan S, Ramasamy C (eds) Agriculture 2000. Tamil Nadu Agricultural University, Coimbatore, pp 36–46
Ramasamy S, ten Berge HFM, Purushothaman S (1997) Yield formation in rice in response to drainage and nitrogen application. Field Crops Res 51:65–82
Randriamiharisoa R, Uphoff N (2002) Factorial trials evaluating the separate and combined effects of SRI practices. In: Uphoff N et al (eds) Assessment of the system of rice intensification: proceedings of an international conference, Sanya, China, April 1–4, 2000. Cornell International Institute for Food, Agriculture and Development, Ithaca, pp 40–46
Randriamiharisoa R, Barison J, Uphoff N (2006) Soil biological contributions to the system of rice production. In: Uphoff N et al (eds) Biological approaches to sustainable soil systems. CRC Press, Boca Raton, pp 409–424
Sato S (2006) An evaluation of the system of rice intensification (SRI) in Eastern Indonesia for its potential to save water while increasing productivity and profitability. Paper for international dialogue on rice and water: exploring options for food security and sustainable environments, IRRI, Los Baños, March 7–8
Sheehy JE, Peng S, Dobermann A, Mitchell PL, Ferrer A, Yang J, Zou Y, Zhong X, Huang J (2004) Fantastic yields in the system of rice intensification: fact or fallacy? Field Crops Res 88:1–8
Sinclair TR (2004) Agronomic UFOs waste valuable scientific resources. Rice Today 3:43
Sinclair TR, Cassman KG (2004) Agronomic UFOs. Field Crops Res 88:9–10
Singh SK, Talati J (2005) Impact of the system of rice intensification (SRI) on rice yields: results of a new sample study in Purulia District, India. IWMI-Tata Water Policy Research Report 47, International Water Management Institute, India Program, Anand
Stoop W, Kassam A (2005) The SRI controversy: a response. Field Crops Res 91:357–360
Stoop W, Uphoff N, Kassam A (2002) A review of agricultural research issues raised by the system of rice intensification (SRI) from Madagascar: opportunities for improving farming systems for resource-poor farmers. Agric Syst 71:249–274

Subbiah SV, Mahendra Kumar K, Bentur JS (2006) DRR's experience of SRI method of rice cultivation in India. Paper for international dialogue on rice and water: exploring options for food security and sustainable environments, IRRI, Los Baños, March 7–8
Surridge C (2004) Feast or famine? Nature 428:360–361
Tao L-X, Wang X, Min S-K (2002) Physiological effects of SRI methods on the rice plant. In: Uphoff N et al (eds) Assessment of the system of rice intensification: proceedings of an international conference, Sanya, April 1–4, 2000. Cornell International Institute for Food, Agriculture and Development, Ithaca, pp 132–136
Tech C (2004) Ecological system of rice intensification (SRI) impact assessment. CEDAC Field Document, Cambodian Center for Study and Development of Agriculture, Phnom Penh
Thiyagarajan TM, Ranganathan CR, Bhaskaran A, Mathan KK, Karivaradaraju TV (2000) Trends in rice area, production and productivity in the different agroclimatic zones of Tamil Nadu. Madras Agric J 87:4–6, 287–290
Thiyagarajan TM, Senthikumar K, Priyadarshini R, Sundarsingh J, Muthusankaranarayanan, Hengsdijk H, Bindraban PS (2005) Evaluation of water saving irrigation and weeder use on the growth and yield of rice. In: Thiyagarajan TM, Hengsijk H, Bindraban PS (eds) Transitions in agriculture for enhancing water productivity. Proceedings of the international symposium on Transitions in agriculture for enhancing water productivity, September 2003, Killikulam, Tamil Nadu, India, pp 3–18
Turner BL, Haygarth PM (2001) Phosphorus solubilization in rewetted soils. Nature 411:258
Uphoff N (2003) Higher yields with fewer external inputs? The system of rice intensification and potential contributions to agricultural sustainability. Int J Agric Sustain 1:38–50
Uphoff N (2005) Possible explanations for the productivity gains achieved with the system of rice intensification (SRI). In: Thiyagarajan TM, Hengsijk H, Bindraban PS (eds) Transitions in agriculture for enhancing water productivity. Proceedings of the international symposium on Transitions in agriculture for enhancing water productivity, September 2003, Killikulam, Tamil Nadu, India, pp 45–70
Uphoff N, Fernandes ECM, Yuan L-P, Peng J-M, Rafaralahy S, Rabenandrasana J (eds) (2002) Assessment of the system of rice intensification: proceedings of an international conference, Sanya, April 1–4, 2000. Cornell International Institute for Food, Agriculture and Development, Ithaca. http://www.ciifad.cornell.edu/sri/proc1/index.html
Wang X-H, Peng J-M (2003) A comparison between system of rice intensification and conventional cultivation methods. Report for China National Hybrid Rice Research and Development Center, Changsha
Wang S-H, Cao W-X, Jiang D, Dai T-B, Zhu Y (2002) Physiological characteristics and high-yield techniques with SRI rice. In: Uphoff N et al (eds) Assessment of the system of rice intensification: proceedings of an international conference, Sanya, April 1–4, 2000. Cornell International Institute for Food, Agriculture and Development, Ithaca, pp 116–124
Yanni YG et al (2001) The beneficial plant growth-promoting association of *Rhizobium leguminosarum* bv. trifolii with rice roots. Austral J Plant Physiol 28:845–870
Yuan L-P (2002) A scientist's perspective on experience with SRI in China for raising the yields of super hybrid rice. In: Uphoff N et al (eds) Assessment of the system of rice intensification: proceedings of an international conference, Sanya, April 1–4, 2000. Cornell International Institute for Food, Agriculture and Development, Ithaca, pp 23–25
Zheng J-G, Lu X-J, Jiang X-L, Tang Y-L (2004) The system of rice intensification (SRI) for super-high yields in rice in Sichuan Basin. In: Poster for 4th International Crop Science Congress, Brisbane. http://www.regional.org.au/au/cs/2004/poster/2/3/ 319_zhengjg.htm
Zhu D-F, Cheng S-H, Zhang Y-P, Lin X-Q (2002) Tillering patterns and the contribution of tillers to grain yield with hybrid rice and wide spacing. In: Uphoff N et al (eds) Assessment of the system of rice intensification: proceedings of an international conference, Sanya, April 1–4, 2002. Cornell International Institute for Food, Agriculture and Development, Ithaca, pp 125–131
Zhu D-F, Lin X-Q, Tao L-X, Zhang Y-P, Lu S-H, Jin X-Y (2004) Effects of SRI methods on rice yield and water saving in China. In: Abstract for World Rice Research Conference, Tsukuba, November 4–7, 2004
Zhu D-F et al (2006) The theory and practice of SRI (in Chinese). China National Rice Research Institute (in press)