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REVIEW ARTICLE

A review of the system of rice intensification in China

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Abstract
Background Continually increasing food demand from a still–growing human population and the need for environmentally–friendly strategies for sustainable agricultural development require innovation and further enhancement of cropping systems' factor productivity. The system of rice intensification (SRI) has been proposed as a suitable strategy to improve rice yields with reduced input requirements, most notably water and seed, while enhancing soil and water quality because agrochemical applications can be cut back.
Scope and conclusions This review examines the performance of SRI methods in China since first introduced in 1999 and considers their implications for further agricultural systems development. A meta–analysis of studies conducted over the past decade in China indicates that SRI methods have been increasing rice yield in comparison trials with current improved practices by more than 10 %. These higher yields are being attained with reduced field requirements for irrigation water and with much–reduced seed rates. This can lower farmers' costs of production and enhance their net income from rice. Such benefits are accompanied by other advantages reported by various researchers in China and elsewhere, such as greater disease resistance, higher nitrogen use efficiency, enhanced photosynthetic rates, and improved physiological traits.

With appropriate modifications for local conditions, there is increasing evidence that SRI principles and practices can offer an environment–friendly strategy for sustainable agriculture in China and elsewhere. This review considers Chinese and other research on opportunities for improving agricultural production and food security with less strain on environmental resources, and for helping farmers cope with increasing climatic stresses now and in the future.

Keywords Climatic change · Crop production · Food security · Low–input production · Rice · Sustainable agricultural intensification

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Introduction

Global food production must increase significantly to meet expected demand by 2050 as the world's populations and their consumption of food, especially animal protein, are still increasing at a substantial rate under conditions of changing climate and growing competition for land, water, labor and energy (Bruinsma 2009). The challenges of meeting high grain demand and securing global food supply are increasingly recognized by various levels of policy makers and scientific communities (Godfray et al. 2010). High–yielding technologies suitable for intensive farming systems need to be developed and adapted to a wide range of environments in developing and in lesser–developed countries (Tilman et al. 2002; Chen et al. 2014), although there is not yet consensus on what kind or kinds of intensification should be pursued.

Rice, the world's major food grain for more than a third of the world's population, is also the greatest consumer of water among all crops, using about 80 % of the total irrigated freshwater resources in Asia (Bouman and Tuong 2001). With decreasing availability of irrigable agricultural land because of degraded land quality and/or water constraints, reaching ever–higher grain production levels will make imperative the more efficient use of our land and limited water supplies (Belder et al. 2005). Producing more rice with minimum water and with less use of synthetic fertilizers as well as less land area is important for the sustainability of rice production systems in the future (Belder et al. 2005; Mueller et al. 2012; Wu and Ma 2015).

A cultivation methodology called the System of Rice Intensification (SRI), developed in Madagascar for irrigated rice during the 1970s and 1980s, has been found to improve rice yields while offering also other benefits including water–saving, cost–reduction, and resistance to biotic and abiotic stresses (Barah 2009; Kassam et al. 2011; Uphoff 1999, 2003, 2012). Since SRI was assembled some 30 years ago (Laulanié 1993), its methods have evolved into a diversifying production system that has produced beneficial results in over 50 countries, including China (http://sri.ciifad.cornell.edu/countries/index.html). SRI concepts and practices have also been extrapolated for application to rainfed rice production and to other crops (Abraham et al. 2014).

The methodology of SRI is based on certain practices, some of them counter–intuitive, in particular: (1) transplanting rice seedlings at a very early age, quickly, and in a careful manner; (2) greatly reducing hill density and plant populations m^{-2} by >80 %; (3) improving soil conditions with inputs of organic matter in preference to inorganic fertilizer, although this can be used in SRI production; (4) reduced applications of irrigation water by careful management, maintaining paddy soils in mostly aerobic condition, and (5) weed control that actively aerates the surface soil rather than relying on herbicides (Stoop et al. 2002; Mati et al. 2011; Stoop 2011). There is some factorial–trial evidence of synergy among these practices (Uphoff and Randriamiharisoa 2002), but not yet agreement in the literature on these relationships (Dobermann 2004; Sheehy et al. 2004). Positive feedback between root and shoot development is an evident factor in SRI results (Mishra et al. 2007; Zhao et al. 2009b; Thakur et al. 2010a; Stoop 2011).

This review evaluates the performance of SRI methods in terms of its benefits, adaptations and modifications in China since first introduced in 1999; and considers obstacles and opportunities for further development of SRI in China.

The introduction of SRI in China

Evaluations of SRI methods began after Chinese researchers learned about the principles and merits of SRI from an article in the ILEIA magazine (Rabenandrasana 1998), which was followed by an article appearing in the Chinese journal *Hybrid Rice* (Yuan 2001). There were also seminars on SRI given by Prof. Uphoff at China Agricultural University and Nanjing Agricultural University in December 1998, and then another by him at the International Rice Research Institute (IRRI) in March 1999 which made SRI a more known phenomenon among rice scientists (http://sri.ciifad.cornell.edu/countries/china/index.html).

The first SRI trials in China were started in 1999 at Nanjing Agricultural University, followed by trials by the China National Hybrid Rice Research and Development Center (CNHRRDC) in Changsha and Sanya.[1] Trials were also undertaken at the China National Rice Research Institute (CNRRI) in Zhejiang province (Tao et al. 2002; Zhu et al. 2002) and at Sichuan Academy of Agricultural Sciences (SAAS)

[1] A first international conference on SRI was held in Sanya, China, April 2002, hosted by Prof. Yuan Longping and cosponsored by his CNHRRDC, the CNRRI, and the Cornell International Institute for Food, Agriculture and Development (CIIFAD), with support from the Rockefeller Foundation and Rural Development Department of the World Bank (http://sri.ciifad.cornell.edu/proc1/index.html). See the keynote presentation by Yuan (2002).

(Zheng et al. 2004). Contributions to the SRI literature have now come from researchers in agricultural universities and academies of science all across China.[2]

Yield improvements with SRI methods and their spread in China

A meta–analysis of comparative yield results

A meta–analysis was undertaken for this review to assess the measured differences in grain yield between SRI and current improved practices in China, to determine how much evidence there is to support the claims made about SRI yield advantage. A comprehensive literature search was conducted of the internet databases of the Web of Knowledge, Google Scholar, and China National Knowledge Infrastructure (www.cnki.net), with 'system for rice intensification' and 'China' entered as keywords.

The criterion for including an article in the meta–analysis database was whether it contained detailed data on rice yields, comparing SRI with specified current improved practices, from field experiments which had been conducted in an acceptable scientific manner. No consideration was given in selection to what the results of the evaluation had been. The standards for comparison were not all the same because evaluators chose whatever current improved practices they wanted to consider as a baseline for their assessment. However, the yields reported for the trials' control practices indicate they were modern improved practices rather than in the category of farmer practice.

Using the criterion of having comparable and detailed data that would permit quantitative analysis and comparison, a total of 17 articles were selected and used for the meta–analysis (listed in Table 1). They provided data on 26 sets of comparative field trials conducted in Zhejiang, Sichuan, Jiangsu, Hunan, Guangdong, Guangxi, and Guizhou provinces, representing China's major rice–producing provinces (geographical distribution shown on map in Fig. 1). In some of the 26 locations, researchers have evaluated several sets of SRI practices such as combining different nutrient management, water management, planting density, and weed control strategies to compare with current improved practices, so there were actually 64 pairs of data for comparative analysis.

The meta–analysis was conducted using a meta–analytical software package (Metawin 2.1, Sinauer Associates, Inc., Sunderland, MA, USA) (Rosenberg et al. 2000; Feng et al. 2008). To estimate the SRI effect compared with current improved practices in term of rice yield, the natural log of the response ratio (R = variable in SRI/current improved practice) was used as the metric for analysis (Hedges et al. 1999), and it is reported as the percentage changes from control as (R–1)×100 % (Ainsworth et al. 2002). A positive percentage change indicates an increase on the SRI plot compared with the yield from current improved practice, while a negative value indicates a decrease.

The meta–analysis used an unweighted approach in which the variance of the effect size was calculated using resampling techniques after 9999 iterations (Ainsworth et al. 2002; Feng et al. 2008). Confidence limits around the effect size were calculated using a bootstrap method (Rosenberg et al. 2000). Estimates of the effect size were assumed to be significant if the 95 % confidence intervals (CI) did not overlap zero (Curtis and Wang 1998).

First, we used the pooled data to determine the average yield increase percentage with SRI practices compared with current improved practice, not making any categorizations. Overall, SRI practices significantly increased the rice yield by 10.9 % compared with current improved practice, with a 95 % CI of 7.6–14.1 %. These yield pairings and comparisons are shown graphically in Fig. 2, with an average SRI yield of 8.3 t ha^{-1} and average control yield of 7.5 t ha^{-1} shown in the inset.

The ratio of increased SRI–to–current improved practice yield was possibly underestimated in this analysis because SRI is best understood and utilized as an integrated package of the practices that are described previously. Many of the trials included in the meta–analysis did not comprehend or include the complete concepts and practices of SRI methodology when they were designed and conducted. So evaluations were made of only partial SRI practice, e.g., with no active

[2] Since 2010, the SRI International Network and Resources Center (SRI–Rice) at Cornell University which disseminates SRI knowledge worldwide has been collecting research reports related to SRI in China, as well as other countries, on its website at: http://sri.ciifad.cornell.edu/countries/china/research/index.html. It maintains also a RefWorks indexing of Chinese research that has reported on SRI effects and variations: http://www.refworks.com/refworks2/?site=010271135918800000%2fRWWS5A696889%2fChinese+SRI+Articles. See analysis of >300 articles on SRI published in the Chinese literature, see Fang and Styger (2014).

Table 1 Summary of the effects of SRI on rice grain yield and related traits compared with current improved practices in China

Study site	Study year	Other treatments	Impact of SRI	References	Comments
Zhejiang, Jiaxing	2010–2011	Establishment methods	SRI increased grain yield (GY) by 14% under mechanical transplanting and conditional transplanting methods rather than under seedling broadcasting and direct–seedling methods. SRI increased P_n and biomass before heading	Chen et al. (2013)	
Zhejiang, Hangzhou	2002–2003	Hill density	SRI increased GY by 12.5%, also with increasing P_n, SLW, LAI and leaf N content	Lin et al. (2005b)	
Zhejiang, Hangzhou	2006–2007	Hill density and N rate	SRI increased GY by 15% with increasing N accumulation	Lin et al. (2009)	
Zhejiang, Hangzhou	2006–2007	Water management	SRI increased GY by 11% with increasing biomass production, LAI, and number of actinomycetes in the rhizosphere soil	Lin et al. (2011)	Actinomycetes are indicators of aerobic soil biota
Zhejiang, Hangzhou	2005–2006	N rate	SRI enhanced GY by 21.5% with increased HI and PFP of applied N and improved WUE	Zhao et al. (2009a)	
Zhejiang, Hangzhou	2005		SRI enhanced GY by 13%, accompanied with increased N, P, K accumulation, except during tillering stage, and improved WUE	Zhao et al. (2011)	
Zhejiang, Hangzhou	2004		SRI enhanced GY by 26.4%, with improved WUE by 91% and microbial biomass C/N	Zhao et al. (2010)	
Zhejiang, Cangnan	2006–2007		SRI decreased GY by 4.4% and lowered production costs by 27.6%, increased net income	Lin et al. (2008)	
Zhejiang, Xianliang	2006		SRI enhanced GY by 8% and increased spikelets per panicle by 9%	Wu (2007)	
Zhejiang, Wenzhou	2003	Varietal evaluations	SRI enhanced GY by 10.6%, accompanied with increased net income, decreased production cost	Lin et al. (2005a)	
Jiangsu	2002		SRI enhanced GY by 8.5%, accompanied with increased spikelets per panicle	Sheehy et al. (2004)	
Hunan	2002		SRI reduced GY by 8.8%, with decreased GF and spikelets per panicle	Sheehy et al. (2004)	
Guangdong	2002		SRI enhanced GY by 0.8%, accompanied with increased GF and decreased panicles per unit area	Sheehy et al. (2004)	
Sichuan and Chongqing	Since 2001		SRI enhanced GY by 31% and its diffusion spread to an area of., application area have reached to 66 700 ha till 2009	Lu et al. (2013)	Triangular culti–vation with SRI
Jiangsu Jiangyin	1999–2001	Varietal evaluation	SRI decreased GY by 5% for Indic rice, while increased GY by 2.3% for Wuyuegeng 9; enhanced root viability, contents of soluble sugar, non–protein N, high partitioning efficiency of carbohydrate and N	Wang et al. (2003)	Four field trials; unpublished data added to analysis in these trials
Sichuan	2001–2012		SRI enhanced GY by 21.7% with increased LAI, WUE and net income. In 2012, the diffused area reached to 400 000 ha	Zheng et al. (2013)	Triangular culti–vation with SRI
Guangxi	2003	Hill density	SRI increased GY by 16%	He et al. (2004a)	
Sichuan	2002	Hill density	SRI enhanced GY by 18%, accompanied with improved rice quality and P_n	Xu et al. (2005)	
Guizhou	2003	Variety	SRI increased GY by 13%	Zhu (2006)	Triangular culti–vation with SRI

Table 1 (continued)

Study site	Study year	Other treatments	Impact of SRI	References	Comments
Guizhou	2002	Varietal evaluation	SRI decreased GY by 2.6%	Zhu (2006)	
Sichuan	2003	Soil fertility	SRI increased GY by 9% under high soil fertility and had no effect under low soil fertility	Zhu (2006)	
	2001		First introduction of SRI's concept to China	Yuan (2001)	
Sichuan	2003	Hill density	SRI significantly enhanced GY, accompanied with increased root dry weight, physiological activity, P content, and exudation intensity	Xu et al. (2003)	
Zhejiang, Hangzhou	2004	N managements	SRI significantly enhanced GY, with increased NO_3–N content, N use efficiency, and quantity of bacterium and actinomycetes in soil	Chen et al. (2007)	
Zhejiang, Hangzhou	2004		SRI significantly increased quantity of microorganisms, microbial biomass C/N, soil enzyme activity, and soil available N and P	Zhao et al. (2009b)	

soil aeration during weeding that would stimulate the abundance and diversity of aerobic soil organisms.

Thus, we undertook to categorize the SRI–practice trials in the pooled sample into three classes: 'good' SRI practice (≥20 points), 'median' SRI practice (15–19 points), and 'minimal' SRI practice (10–14 points). The scoring and classification were done according to the matrix presented in Table 2, which was formulated based on SRI principles and precepts. The table gives the point values for different practices, arrayed along a continuum from 0 to 3 points for land preparation practices, nursery management, transplanting practices, age of seedlings, number per hill, planting density, water management, nutrient management, and weed control.

When the pooled sample was disaggregated in this way, it was seen that the magnitude of the increases in rice yield under 'good' SRI practice was highest (20.3 %, with a CI of 16.7 to 24.2 %). 'Median' SRI practice also gave a significant increase in rice yield compared with current improved practice, by 12.0 %, with a CI of 8.2–15.8 %. However, this yield enhancement was significantly lower than that achieved with 'good' SRI practice, as seen in Fig. 3.

Of particular relevance is that 'minimal' use of SRI practices, which employed only some or a few of the recommended practices, had the effect of significantly *decreasing* rice yield compared to the control practices, by 3.9 %, with a CI of −7.0 to −0.5 %. Considering this category of minimal/partial SRI practice separately from the other trials indicated that missing some or many of the components of SRI practice will negate the positive effects from utilizing the more complete SRI methodology compared with current cultivation practices.

The meta–analysis had a further important implication. In evaluating the published results of SRI trials in China, we found that in none of the studies in the pool drawn from previous Chinese research had the full recommended SRI protocol (column 1 of Table 2) been used, e.g., soil fertilization was not predominantly organic, or herbicides were used instead of soil–aerating weeding, so the practices evaluated would not have fully mobilized the potential benefits from aerobic soil organisms.

This suggests that the full use of SRI recommendations could produce even greater yield gains, but as this was not evaluated, no conclusion can be drawn. We can point this out as a possibility to be investigated. As seen in Table 1, more complete utilization of SRI principles for rice production in Sichuan province, China has made

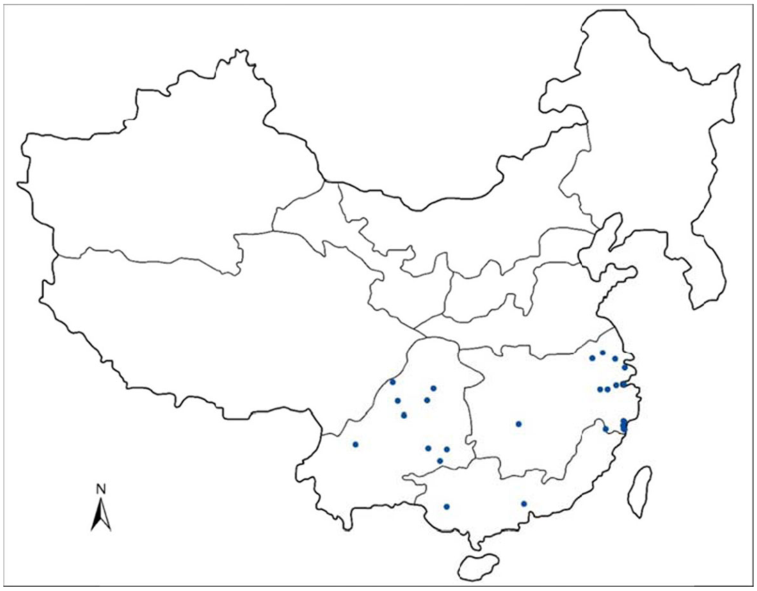

Fig. 1 Geographic locations of SRI–evaluation comparative trials conducted across the main rice–growing regions of China

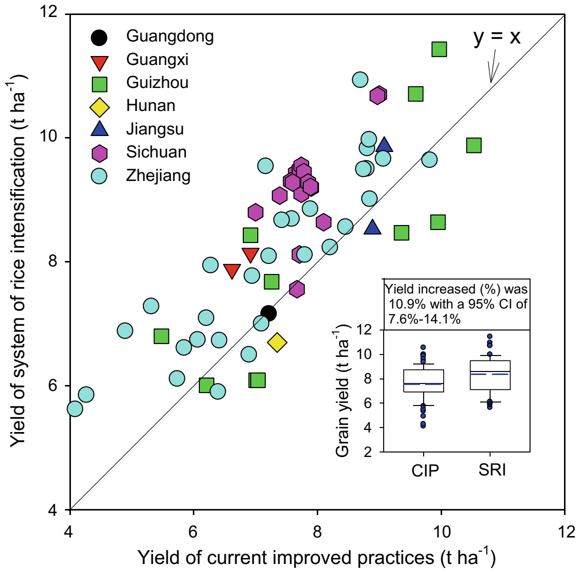

Fig. 2 A distributed plot showing the paired grain yields of system of rice intensification (SRI, y axis) and current improved practices (CIP, x axis) from articles that met the selection criteria for meta–analysis, and inserted box–plot showing the yield advantage of SRI over CIP. Scatter points above the diagonal line indicate yield advantage of SRI over CIP. The 26 field trials from which data were reported in the 17 articles identified from the database searches were conducted in Zhejiang, Sichuan, Jiangsu, Hunan, Guangdong, Guangxi, and Guizhou provinces, shown in Fig. 1. Sources: Data from Chen et al. (2013); He et al. (2004a); Lin et al. (2005a); Lin et al. (2005b); Lin et al. (2008); Lin et al. (2009); Lin et al. (2011); Sheehy et al. (2004); Wang et al. (2003); Wu (2007); Xu et al. (2003); Xu et al. (2005); Zhu (2006); Zhao et al. (2009a); Zhao et al. (2010); Zhao et al. (2011); and Zheng et al. (2013)

it possible to enhance yields by up to 30 % with adapted SRI alternative management methods.

Uptake of SRI methods within China

Through the efforts of Chinese rice scientists working in research institutes such as CNRRI and SAAS, in universities, and in other government organizations such as provincial departments of agriculture, SRI practices have been spreading, and they are used, at least partially if not yet fully, on a large part of the rice production area in several provinces, most notably Sichuan and Zhejiang.

- By 2012, the area under SRI in Sichuan Province (total rice harvested area, 2 million ha in 2012) had reached almost 400,000 ha, having started from a base of only 1132 ha in 2004. Average SRI yields during this period were over 9 t ha^{-1}, more than 1.6 t ha^{-1} above the province's already high average paddy yield of 7.6 t ha^{-1} according to Provincial Department of Agriculture data. This increase was achieved with a 25 % reduction in the irrigation water required per hectare (Zheng et al. 2013).
- Recent figures are not available from Zhejiang, but the area under SRI methods in that province due to successful extension programs there had reached 110,000 ha in 2007 (Zhu 2006). This is quite close to the corresponding figure for Sichuan in that year, 117,267 ha.

Table 2 Scoring matrix for kinds and degrees of System of Rice Intensification (SRI) crop management, developed to differentiate full use of SRI methods from non–use of these methods, with intermediate degrees of utilization; System Rice Intensification (SRI) scoring method and SRI characterization–by kind and by degree

Practice	Score			
	3	2	1	0
Land preparation	Soil is well–worked and well–leveled	Soil is reasonably well–worked and leveled	Soil is minimally worked and leveled	Soil is not well–worked and not well–leveled
Nursery management	Nursery has good soil material and is well–drained	Nursery has acceptable soil material and is not flooded	Nursery has acceptable soil material but is flooded	Nursery has poor soil and/or is kept continuously flooded
Transplanting practice	Seedlings removed gently from nursery, transplanted gently within 30 min	Seedlings carefully removed and trans–ported, transplanted within 1 h	Seedlings removed with minimal care, transplanted within 3 h	Seedlings removed without care, transplanted more than 3 h
Age of seedlings	8–10 days	10–15 days	15–20 days	Over 20 days
Number per hill	1 per hill	2 per hill	3 per hill	4 or more per hill
Planting density	9–16 plants/m^2	17–25 plants/m^2	26–40 plants/m^2	Over 40 plants/m^2
Water management	'Minimum of water' carefully applied	Well–managed AWD	AWD without careful management	Continuous flooding
Nutrient management	Full organic fertilization[a]	More organic than chemical fertilization	More chemical than organic fertilization	Full chemical fertilization
Weed control	4 cono–weedings	2–3 cono–weedings	1 cono–weeding or manual weeding	Herbicide use

Maximum score for 'ideal' SRI would be 27. 'Good' SRI scored 20 points of above. 'Median' SRI was 15 to 19 points, while 'minimal' SRI was 10–14 points. Below 10 points cannot be considered as SRI. Many rice production systems will have some elements of SRI practice since this methodology is a matter of degree rather than a dichotomous phenomenon, with only 'SRI practice' or 'not–SRI.' This matrix developed for this meta–analytical exercise can have more general use

[a] This refers to fully organic SRI. Integrated nutrient management which seeks to find and utilize optimizing combinations of organic and inorganic nutrient sources may give higher yields than 100 % organic fertilization (Lin et al. 2011)

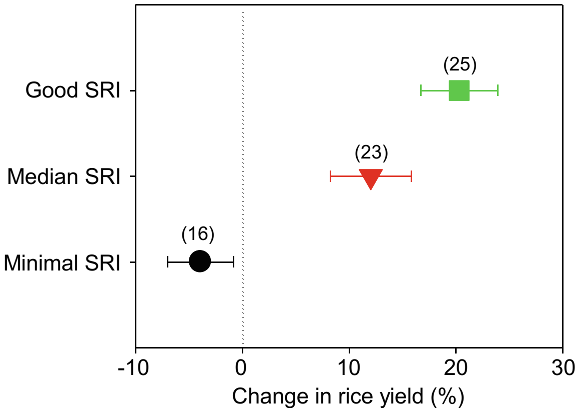

Fig. 3 Effect of system of rice intensification (SRI) on rice yield (in %) in comparison with current improved practices when SRI practices were categorized into three classes: good SRI, median SRI, and minimal SRI, as explained in text and Table 2. *Error bars* are for 95 % confidence intervals. The number of observations per group is indicated in parentheses; the total number of comparison trials evaluated was N=64

- By 2012, the total estimated area in China overall with adapted SRI practices was considered to have exceeded 900,000 ha, up from 700,000 ha in 2011 and from 200,000+ ha in 2007, according to W.J. Zheng, Institute of Crop Sciences, China Academy of Agricultural Sciences (IRIN 2012).

CNRRI researchers have concluded that grain yields with adapted SRI practices in China are usually 8–11 t ha^{-1}. The data on yield improvement mentioned above and on the spread of these alternative management methods in China have prompted this review of SRI phenomena and scientific assessments. What is reported here may encourage others to engage in further testing and explanation and in more innovation to ascertain the merits and limits of this innovation for the Chinese rice sector and beyond, i.e., for other countries and for other crops.

In the next section, we report on adaptations that have been made by Chinese researchers and farmers to the original SRI paradigm to take advantage of its insights under Chinese conditions and constraints. Then, we review aspects of SRI theory and practice that goes beyond yield improvement since SRI is a multi–dimensional innovation, considering evidence from Chinese and other researchers on economic, environmental and other benefits. Further, we consider obstacles and opportunities regarding the further spread and utilization of SRI ideas and practices in China, with discussion then in a concluding section of implications and further issues.

Adaptations and modifications of SRI practices in China

Several productive adaptations of SRI have emerged in China over the past decade.

Triangular planting

In Sichuan province, a triangular planting system has been developed at Meishan to go with other SRI practices (http://www.ms.gov.cn/info/1149/22043.htm). Three plants are transplanted in widely–spaced hills, 30–40 cm apart, with 7–10 cm distance between the seedlings, rather than clumping them all together as in usual practice. With just 5–6 hills m^{-2} (15–18 plants m^{-2}), the triangular pattern of crop establishment has the same number of plants per m^{-2} as with 'classical' SRI (16 plants m^{-2}), but this configuration is considered more effective for harvesting the lower solar radiation in Sichuan province (Zhu 2006; Lu et al. 2013; Zheng et al. 2013).

An experimental evaluation found standard SRI methods giving a yield of 10.42 t ha^{-1}, 20 % higher than the control yield of 8.65 t ha^{-1} with modern, improved methods and the same variety. However, the 'triangular' planting pattern with approximately 16 plants m^{-2} gave a yield of 13.39 t ha^{-1}, 55 % higher (Zheng et al. 2004). This geometry of crop establishment thus has substantial potential to increase rice crop yields in conjunction with other SRI practices, at least under Sichuan conditions for rice production.

Direct–seeding

In Zhejiang province, in order to reduce labor requirements, farmers here have developed a direct–seeded version of SRI with wide plant spacing, rather than transplanting. It includes also the application of greater amounts of manure; a reduction in the quantity of seed used compared with broadcasted crop establishment (18 kg ha^{-1} instead of 40 kg ha^{-1}); and a decreased amount of water for irrigation. Rice yields of more than 11 t ha^{-1} are being achieved with these modified methods of SRI (personal communication, Gao Songlin, director of the Technology Extension Center, Xiu Zhou county, Zhejiang province; Chen et al. 2013).

Cold–climate adaptations

In Heilongjiang province, a rice cropping system quite similar to SRI, designated as 3–S, was developed in the 1990s by researchers at Northeast Agricultural University before there was any knowledge in China of the Madagascar innovation (Jin et al. 2005). This system aimed to achieve greater yield in cold regions by using widely–spaced hills and low plant density together with high–quality super–rice varieties. 3-S practices including elements of SRI have provided localized rice cultivation methods suited for colder climates, raising paddy yields to 8–9 t ha^{-1} (http://sri.ciifad.cornell.edu/countries/china/china3Ssystem09.pdf).

Wheat–rice farming systems

In Jiangsu province, ideas and features of SRI have been incorporated into a wheat–rice rotational cropping system developed by the Centre for Agro–Ecology and Farming Systems of the Chinese Academy of Agricultural Sciences. This system combines raised beds and mulching with the techniques of SRI to control weeds, prevent soil water evaporation, and thereby to conserve more water in the soil for better germination and growth of the subsequent wheat crop (Zhu 2006; Wang et al. 2003). This adaptation of SRI aims to overcome water constraints, especially for areas under drought or during periods of water shortage, and also to reduce greenhouse gas emissions from paddy fields (Zhang and Lu 2010). To minimize labor requirements, herbicides are applied as necessary to control weeds rather than use hand and mechanical weeding, so the possible SRI benefits from active soil aeration have not been built into this version.

Permanent raised beds with plastic film cover

In Sichuan province, the principles of conservation agriculture (minimum soil tillage, continuous organic matter on the soil, and crop rotation) have been incorporated with SRI methods of young, widely–spaced transplanted seedlings (with triangular planting in hills), increased organic matter, and no inundation (Lu et al. 2013). Plastic film on the beds makes weeding unnecessary, and the proliferation of organisms in the soil improves its structure and provides biologically– rather than mechanically–effected soil aeration. Data from 16 locations in the province showed an average grain yield increase of 2.38 t ha^{-1} with less seed, 10–15 % less fertilizer, about 10 % less input of labor, and water saving of up to 70 %, with drought resilience a notable benefit from this management strategy with SRI methods (Lu et al. 2013).

Such innovations are expected and accepted with SRI methodology because it is not considered as a set technology but rather as a set of ideas and insights for creating better growing environments for rice plants above– and below–ground, aiming for better phenotypic expression of their genetic potentials. Adaptations to local conditions are in effect part of the ‘system’ as originally conceived.

Non–yield effects with SRI methods in China and elsewhere

A variety of evaluations have compared SRI effects with those of present improved rice cultivation practices. Here we review briefly some of the reported impacts that go beyond agronomic yields and range from economic to environmental considerations. In addition to raising yields, mentioned above, and beyond raising economic returns and reducing irrigation water requirements, which are considered below (Table 1), it has been found in China that appropriately modified SRI practices have a number of diverse benefits such as reducing seed requirements by 50–90 % (Lin et al. 2005a); suppressing insect and disease problems, and diminishing the risk of lodging (Fig. 4); increasing nitrogen (N) use efficiency (NUE) (Chen et al. 2007; Zhao et al. 2009a); and improving the photosynthesis rate and other physiological traits of rice plants (Chen et al. 2013; Lin et al. 2005b).

These effects derive from inducing the plants, through modifications in cultural practices, to develop into more productive and more robust phenotypes from their initial genetic endowment (genotype). SRI rice plants have larger, more effective root systems which interact with enhanced populations of beneficial soil microbes (Anas et al. 2011). The contributions made by the latter are becoming better understood in recent years as the plant–soil microbiome which parallels the human microbiome with similar benefits for organisms' growth and health (Chi et al. 2005, 2010; Uphoff et al. 2013; Turner et al. 2014; Gopalakrishnan et al. 2014).

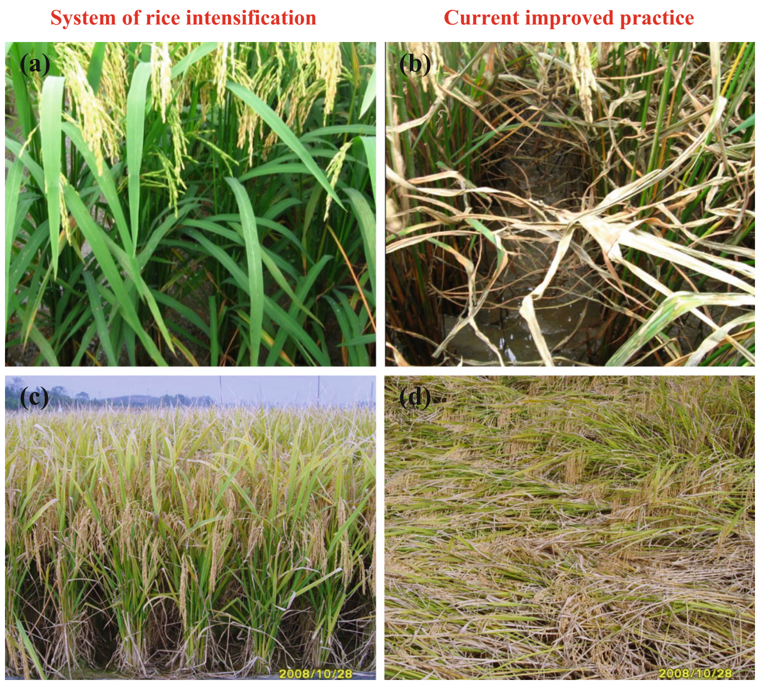

Fig. 4 Field performance of rice crops showing sheath blight resistance and lodging resistance, contrasting system of rice intensification (SRI, **a & c**) with current improved practices (CIP, **b & d**). Rice plants in CIP plots were almost entirely lodged at maturity stage and suffered severe sheath blight damage, whereas rice plants in all the SRI fields were still standing upright after the storm had passed over and were free of sheath blight. Field experiments studying the sheath blight resistance and lodging resistance between SRI and CIP were conducted in farmers' fields during 2008 and 2009 at Dajin Township, Wuxue County, Hubei province, China (29°50′ N; 115°33′ E) (This Figure is adopted from Wu et al. 2015). Two widely adopted commercial F_1 hybrid cultivars (Liangyou–287 and T–you207) were used. Pictures (**a**) & (**b**) were taken in July 2009; (**c**) & (**d**) were taken in October 2008

Economic returns

The economic returns to Sichuan farmers from adoption and adaptations of SRI as evaluated by the Provincial Department of Agriculture are definitely positive, ranging from 750 to 2250 RMB (120–360 USD) per ha. These returns are attributable mostly to the improved grain yield and quality under SRI management, but this advantage is accompanied by reduced costs of production and less requirement of irrigation water and seeds (personal communication, Liu Daiyin, Sichuan Provincial Department of Agriculture; Xu et al. 2005; Lin et al. 2008; Lu et al. 2013).

Water saving

The agricultural sector consumes 80 % of the total fresh water resources in China (Bouman and Tuong 2001). With modified practices of SRI, both total water use efficiency (TWUE) and irrigation water use efficiency (IWUE), were seen in one Chinese evaluation (Zhao et al. 2010) to be higher than with conventional practices, by 91 % and 195 %, respectively, a significant reduction in water consumption. The magnitude of these figures may reflect a considerable overuse of water as the baseline common practice.

A meta–analysis of the water savings and productivity achieved with SRI management across eight countries, including China, considered the results of 251 comparison trials reported in 29 published journal articles (Jagannath et al. 2013). This study calculated an average increase in TWUE of 52 %, and in IWUE of 78 % from using SRI practices, which reflected both reductions in total water and irrigation water applications ha^{-1}, by 22 and 35 %, respectively, accompanying increased paddy yield, by 11 % on average.

Interestingly, the four published studies from China showed an average increase in WUE with SRI methods of 54 % in comparison with conventional practice, which was close to the international average; but in the Chinese evaluations there was an increase of 112 % in IWUE when SRI practices were used, in line with the observation concluding the previous paragraph of relatively more overuse of water than needed for good crop performance.

A 2–year CNRRI evaluation previously cited (Lin et al. 2009) found that higher grain yields of super–hybrid rice could be obtained with concurrent reductions in irrigation water (alternate wetting and drying, AWD, rather than continuous flooding) as well as in seed rate (by 70 % or more), and inorganic N fertilizer (cutting this by 50 % but keeping the rate of N application constant with compensating organic soil amendments). While it is increasingly recognized that decreasing irrigation need not lower paddy yields, with SRI crop management there is not a tradeoff between water applications and grain yield. Yield can be increased with less water, creating a positive–sum rather than a zero–sum relationship with regard to reducing irrigation.

Grain and milling quality

There are also improvements in rice quality attributed to SRI methods. Studies of milling qualities done at Sichuan Agricultural University found that the milling outturn from SRI paddy rice was 16.1 % higher for the same rice variety, and outturn of head rice (unbroken grains) was 17.5 % higher (He et al. 2004b; Xu et al. 2005). At the same time, with SRI management, chalky kernels were reduced by 30.7 % and general chalkiness of grains by 65 %. More research remains to be done on grain quality parameters in China.

Mitigation of climate–change dynamics

SRI management practices have been reported also to have some countervailing effects that reduce irrigated rice paddies' contribution to global warming potential (GWP) by their reducing the emission of greenhouse gases (GHGs). Stopping the continuous flooding of paddies will by all accounts diminish the production of methane (CH_4), reducing the anaerobic soil conditions that favor larger and more active populations of methanogens (Yan et al. 2009). But it has been uncertain whether the more aerobic soil conditions which SRI creates will enhance the emission of nitrous oxide (N_2O). Because this GHG is 25–fold more potent than methane, small increases in N_2O could offset any gains made toward lowering GWP that larger CH_4 reductions might accomplish.

So far, studies evaluating these dynamics have not indicated any significant offsetting N_2O generation, perhaps because SRI practices reduce the soil levels of inorganic N in favor of raising the provision of organic N. Actually, reductions in the application of N fertilizers should diminish emissions of carbon dioxide (CO_2) because much carbon is emitted from producing and transporting N fertilizer (Lal 2004).

A study in China not evaluating SRI management practices as such found that CH_4 emissions can be reduced by one–third simply by drying paddy fields at least once during the growing season (Yan et al. 2009). This is less frequent than with SRI management, so this SRI practice should be able to have a large mitigating impact. That study also found that returning rice straw to the field to enhance soil organic matter also had mitigating effects on GHG emissions. There has been interest within the China Academy of Agricultural Sciences in possible mitigation of global warming dynamics through the integration of SRI methods into the rice–wheat cropping system, which is widespread in China (Zhang and Lu 2010).

We have not found any evaluations of SRI impact on GHG emissions done in China. More evaluation research needs to be done in this area to ascertain the effect of SRI practices on the different GHG emissions because these can vary widely according to soil type, soil moisture, pH, temperature and other factors, and there are complex interactions among them (Setiawan et al. 2014). In any case, no single, summary numbers can be calculated and reported, only ranges and central tendencies according to variations in the relevant parameters. But evidence is accumulating that with SRI management, there can be some mitigating effect on global warming.

Obstacles and opportunities for further development of SRI in China

That the benefits observed and reported from use of SRI's alternative management methods are numerous has, ironically, sometimes made gaining acceptance of SRI more difficult rather than easier. The saying 'too good to be true' has often been applied to SRI to dismiss reports of its effects a priori without their being tested empirically. Even so, dozens and now hundreds of scientists in various countries, starting with China, have conducted studies over the past decade to the point where there is now a very substantial body of literature in the peer–reviewed journals, approaching the point where there can be significant shifts in theory and practice.

SRI practice does not require the use of new varieties or new inputs so much as it involves changing mindsets and modifying the ways that available resources–soil, water, labor, seeds, and capital–are utilized (Kassam et al. 2011). Unfortunately, some of the SRI practices are rather counter–intuitive, even if supported by scientific evidence. Gaining acceptance of these practices–which promise more production from fewer plants, with less water and reduced inputs–has often been difficult and slow, although not always, as seen from experience in Sichuan and Zhejiang provinces

Many questions regarding SRI remain to be researched more thoroughly as it is a work in progress, and some further modifications such as the mechanization of operations like transplanting and weeding will be necessary to get full exploitation of SRI opportunities as discussed below. That China's rice sector faces serious challenges to increase rice productivity while improving its resource–use efficiency and protecting the environment suggests that SRI experience and research be given systematic and scientific consideration. Accordingly, we review in this section some obstacles and opportunities relevant to meeting these challenges.

Slow response to knowledge of SRI

Although farmers in Sichuan and Zhejiang provinces have taken up SRI ideas and practices reasonably rapidly (Chen et al. 2013; Lu et al. 2013), the diffusion of SRI innovations in other regions of China has been hampered by a lack of cooperation among agricultural experts and by limited support from agricultural extension services (Xu et al. 2013). Also as knowledge of these new practices has spread, often farmers have adopted only one, two or three of them, but not the full set, thereby not getting the full agronomic effect of the methodology. This has been seen also in other countries (e.g., Noltze et al. 2012; Plabita and Raj 2014). This means that the full potential of the innovation is not being capitalized upon, which is not unusual as change in agriculture usually proceeds slowly and unevenly. This does not invalidate the innovation itself and, indeed, means that there is potential available still to be exploited. When exposed to new methods and technologies, farmers' responses are not guided solely by their own considerations, but are influenced by what they see and hear from others. And when there is not enthusiasm or even agreement among those who presumably have expert knowledge, this reinforces any disposition not to make changes in familiar practices.

Before SRI ideas were introduced in China, there were already some trends among at least some rice farmers to move toward several key SRI practices. Researchers at CNRRI had observed that already by the time when SRI ideas were introduced, Chinese farmers were beginning to lower their plant densities, reduce their irrigation applications, and transplant younger seedlings, finding some advantage in making these changes even without their being promoted or being linked as they are with SRI (Zhu 2004). A 2–year evaluation by CNRRI researchers with super–rice hybrid varieties showed that higher yields could be attained by using younger seedlings, reduced seed rate, less irrigation, and less fertilizer, applying the same level of N but with equal shares in organic and inorganic forms (Lin et al. 2009). These results indicate that Chinese rice farmers would be more successful by using less seed, less water, and less chemical fertilizer (with more organic matter to support soil health and function).

From conversations with farmers in China, we have found, however, that those who have learned about the new practices but who have not adopted them often thinks that the anticipated net gains were not enough for them to make the extra effort to change their practices. This is not an uncommon rationale for farmers around the world. However, those who have taken up the new methods have found the net gain quite attractive, and thus have seldom given them up, although we have not found systematic studies of adoption or disadoption rates. As with so much innovation, acceptance may be a matter of time, with change possibly accelerated by opportunities to observe, learn, experiment, and evaluate. Also, the attitudes and pronouncements of scientists and policy–makers, if positive, could speed up farmer acceptance and make attainable gains in resource productivity more rapid.

Over–dependence on chemical fertilizers and agrochemicals

There has been little sustained effort in China to shift from a heavy reliance on inorganic soil fertilization, particularly for N, to organic sources and methods, which can be made more productive by using them together with associated SRI practices. Some attempts have started to curb the present heavy utilization of chemical fertilizer and to increase the applications of organic matter through the application of compost or green manures (Zhu et al. 2011). But Chinese farmers and researchers are not yet taking much advantage of the opportunities that SRI concepts offer to reduce, even greatly, their reliance on inorganic fertilizers and also herbicides.

China indeed needs more food (Tilman et al. 2002). However, overuse of inorganic fertilizers and pesticides to increase rice yield has high economic and environmental costs (Chen et al. 2014). Between 1998 and 2012, fertilizer consumption in China had increased by 1.6 times and the use of pesticides went up 5–fold; yet despite so much greater agrochemical inputs, the country's food production increased by only 15 %, reflecting ever–lower marginal resource use efficiency with this kind of input–dependent agricultural production (Zhang et al. 2012; Wu and Ma 2015). Continuing increases in the use of these agrochemicals are yielding less and less benefit per unit applied.

Farmers have all too often responded to these diminishing returns by increasing further their use of agrochemical inputs, even as their costs mount and their benefits decline. Such uneconomic behavior for farmers has great environmental costs for China as it contributes to more and faster accumulation of nitrate in drinking water sources and to the build–up of other toxic substances, harming fish and marine ecosystems and even human health (Chen et al. 2014). Meanwhile, the marginal returns from fertilizer keep diminishing, lowering resource use efficiency even more (Peng et al. 2009; Yan et al. 2013).

SRI management can raise the returns to farmers' use of organic means to enhance and sustain their soil's fertility which will in turn give better economic returns and contribute to environmental quality and sustainability.

Addressing environmental constraints

Global warming will affect rice production adversely and thus have an adverse impact on food security. It has been estimated that for each increase of 1 °C in the growing season's minimum temperature, there will be a corresponding 10 % decline in rice yield (Peng et al. 2004). In addition to increasing paddy yields and reducing costs, SRI methodology if applied on a large scale can offer ways for mitigating global warming and/or adapting to the environmental challenges which the rice sector faces by

- Reducing sector demand for water use;
- Reducing the use of inorganic fertilizers; and
- Reducing greenhouse gas emissions

In addition, rice plants grown with SRI practices, by having stronger tillers and root systems and tougher leaves, are more resistant to the biotic and abiotic stresses that accompany climate change – heat stress, drought stress, flooding, storm, and disease damage – compared to plants grown with conventional cultivation practices (Uphoff et al. 2011; Wu et al. 2015). Differences in rice crop resistance to disease and storm damage as affected by crop management can be seen in Fig. 4.

It is estimated that 24–30 % of the world's accessible freshwater resources are used to irrigate rice, while it is known that agricultural water is becoming increasingly scarce (IWMI 2007). Global warming with its higher temperatures will further increase crops' water requirements, thus making current water shortages and uncertainties ever more serious. Means to increase water use efficiency in rice production must be found in both irrigated and rainfed regions. With SRI methods, water use for irrigated paddy cultivation can be substantially reduced, mentioned above. Making water savings can enable rice and other crops to continue being grown in regions experiencing diminishing water availability (Satyanarayana et al. 2007).

Standard agricultural practices which now depend heavily on inorganic fertilizers have become a major factor in increasing the emissions of CO_2 and N_2O. These greenhouse gases contribute to global warming, but nitrous oxide also increases the environmental hazard of acid rain, with nitrate accumulating in water systems, polluting drinking water, and compromising marine ecosystems (Zhang et al. 2012; Yan et al. 2013). There are win–win possibilities with SRI methods. By relying as much as possible on organic matter to enhance soil fertility, thereby reducing their use of inorganic fertilizers, farmers can improve the structure and functioning of their soils and can increase their resource–use efficiency (Uphoff et al. 2006).

More use of organic materials to enhance and sustain soil fertility under SRI practices might also increase the carbon sinks and C sequestration in erodible soil. This is important because soil carbon is gradually being lost into the atmosphere, contributing to global climate change, while valuable topsoil continues to be reduced through wind and water erosion. Currently, Chinese farmers are adopting SRI more for economic reasons than out of environmental concerns (Zhu et al. 2011). However, with the diffusion of SRI in China, economic and environmental benefits could reinforce each other, rather than being regarded as being mutually–exclusive, i.e., zero–sum, with ultimately negative–sum consequences.

Reducing labor requirements with SRI

Changing demographics in rural areas, and especially in China, will require further reductions in the agriculture sector's requirements for labor, thereby creating general incentives for more mechanization of production practices (Xu et al. 2013). SRI, at least initially during the learning period, requires some additional labor, which creates an apparent barrier for its adoption because of the high cost and limited availability of agricultural labor in the countryside. Actually, a study by China Agricultural University researchers of SRI adoption in a Sichuan village (where SRI use had increased from 8 farmers in 2004 to 395 farmers in 2005) found that the most frequent reason which these farmers gave for accepting SRI methods was their reduction in labor requirements, appreciated more than the resulting yield increases (47 %) or water savings (45 %) (Xu et al. 2006). However, in any case, the intersections of labor supply and demand and of labor costs and returns need to be addressed for SRI to gain wider acceptance.

The mechanization of production practices has become dominant in much of the agricultural sector in China and in the rest of the world due to growing labor shortages. For broader adoption of SRI methods, some degree of mechanization is essential, but this should be possible. Chinese engineers should be able to design weeding implements that can be mounted on two–wheeled tractors, which could weed multiple rows at one pass with their powered tillage ensuring good aeration of the soil's surface. Given that so few seedlings are needed with SRI methodology, it also should be feasible to design and build implements that can transplant young seedlings with minimal trauma and at precise spacing.

Although SRI was originally developed to benefit small, resource–limited farmers, it can also be adapted to meet the needs of farmers with greater resources. Practices such as wider spacing of young seedlings, one seedling per hill, reduced water applications, mechanical weeding, and soil aeration are all amenable to mechanized methods. As a successful case study in Pakistan's province of Punjab, a mechanized version of SRI was first evaluated on an 8–hectare, laser–leveled test field. The methods and machines together were able decrease labor and water requirements both by 70 % compared to conventional practice, with an impressive grain yield of 12 t ha^{-1} (Sharif 2011). Its demonstration might have more potential in China if it is applied at a large scale.

SRI approaches to growing rice should be more amenable to mechanization than is traditional lowland paddy production because it is difficult for machines to operate under flooded–field conditions and to carry out the dense planting currently favored. There are good reasons to believe that in the near future, mechanized transplanting and other labor–saving machines can be successfully adapted for SRI principles and practices within the rice sector of China and elsewhere.

One way to cope with problems of labor cost and scarcity in rice cropping was discussed previously, developing direct–seeding techniques that make nursery preparation and management as well as transplanting unnecessary (Huang et al. 2011).

The most common direct–seeding technique involves broadcasting 40 to 60 kg seeds ha^{-1} of seeds on to recently–drained, well–puddled seedbeds or into shallow standing water on the fields under conventional practice. Such a high seed rate used with direct–seeding is, however, the converse of SRI practice, which reduces plant populations m^{-2} to allow more room for the growth of individual plants, resulting in higher yields both from individual hills and also m^{-2} (Thakur et al. 2010b). With SRI principles in mind, a technology has been developed in India and Sri Lanka to reduce labor requirements for SRI, doing direct–seeding by pulling wheeled–drums across rice paddies in parallel rows (Reddy et al. 2012), that can be accessed to China, with a significant decrease in seed use of about 20–25 kg of seed ha^{-1}.

Modifications within cropping systems: ratooning and seedling age

There are also other ways in which SRI strategy can be applied to raise rice yields with a reduction in inputs. One innovation being developed in China is the ratooning of rice crops following SRI principles. With ratooning, a second harvest is obtained from the growth of the parent crop. This makes it possible to produce more rice with less labor input per kg of paddy harvested because there is no need to plant the second crop. Even if the yield is not as high as obtained from a first crop, the substantial reduction in labor costs can make the rice production more profitable (Xiong et al. 2000; Santos et al. 2003).

This practice, now being used more widely in cooler areas of China, is particularly suitable for SRI adaptations because of the stronger and deeper root systems of rice plants grown under SRI management (Barison and Uphoff 2010). Such plants can ratoon (re–grow) better than conventionally–cultivated rice. Ratooning of rice under SRI could be practiced in most rice–growing areas of China such as Fujian, Zhejiang, Jiangsu, Sichuan, Hunan, Guangdong and Hubei provinces which have sufficient heat and radiation resources for such a cropping system (Xiong et al. 2000).

Our experiments in Hubei province have shown that a yield of 5.0 t ha^{-1} is attainable from ratooned rice following a yield of 10 t ha^{-1} from the main–season rice harvest with SRI management. A ratooned yield of more than 6 t ha^{-1} has been reported from Fujian province (Zhu and Chen 2006). Some ratooned SRI rice experiments in Indonesia have achieved second–crop yields almost 70 % of their first harvest, giving a significantly higher yield than from ratooned rice grown with conventional methods (Iswandi et al. 2014). Growing ratooned rice with two harvests from one planting, where the second harvest is enhanced by the deeper growth and greater longevity of SRI rice roots, should be attractive to farmers who want to reduce their labor inputs compared to the usual requirements for growing double–season rice.

Another modification being introduced in China is to accept somewhat older seedling age for rice–wheat and double–rice cropping systems than usually recommended for SRI cultivation. SRI theory and practice indicate that best results come from transplanting rice seedlings before they enter their 4th phyllochron of growth (Stoop et al. 2002). Both rice–wheat or double–rice cropping systems which have two harvests per year are, however, constrained by time–limited temperature resources during the summer growing season, particularly toward its end. Under study conditions, the available land, labor, water and temperature resources can be more efficiently exploited through changes in cultivation practices that diverge from the SRI norm of very young seedlings.

It has been found that extending rice seedlings' period of growth in the nursery can shorten the crop's growth period after transplantation in the field, thereby also reducing crop stresses and losses at the end of the second season (Wu et al. 2015). In these cropping systems, older rice seedlings must be transplanted, more than 30 days old. This goes against SRI precepts which seek to capitalize upon rice plants' maximum growth potential, which declines after seedlings more than 15 days old are transplanted (Stoop et al. 2002). However, it offers compensating advantages.

Growing conditions in parts of China where the rice–wheat or double–rice cropping systems are practiced present significant problems of timing for transplanting very young seedlings according to SRI theory. These problems do not arise the same way in India or in most of South Asia and Southeast Asia because their climates are warmer overall, and also for a longer time. One of our previous studies suggests that given the very low temperatures prevailing in parts of China during the vegetative growth stage of rice seedlings in the early–rice season or toward the end of the second season in double–rice cropping, better performance can be attained from seedlings that are 28 days old (considerably younger than the 40–day seedlings currently used) in comparison with seedlings that are only half as old (14 days) which are less cold–tolerant (Wu and Ma 2015).

In phenological terms, a 28–day rice seedling in some regions of China may be not much older biologically than a 15–day seedling in Sumatra or Java near the equator. In more northerly Japan and in elevated regions of eastern India, Chapagain and Yamaji (2010) and Deb et al. (2012) have found that transplanting seedlings about 20 days old with SRI methods can give grain yield gains comparable to those attained elsewhere from younger seedlings that are just 15 days old. Cooler or cold temperatures can make even 20–30 day seedlings phenologically equivalent to 10–15–day seedlings in warmer climates.

Optimal seedling age thus needs to be considered within the context of particular cropping systems, as was recognized by SRI's originator (Laulanié 1993). In the double–rice cropping system, the productivity of the second crop is held hostage to the possibility that temperatures toward the end of its second growing season will drop enough to interfere with ripening and ultimate grain yield. Starting the second crop with older seedlings than ideal for SRI practice can advance the phenological development of the plants so that they can more assuredly complete their crop cycle. Some tradeoff of lower yield is acceptable for greater certainty of harvesting a crop that has benefited from the other SRI practices. Thus, older seedlings beyond the recommended 2–leaf stage may fit better into the seasonal planting schedules for double–rice cropping or in some situations for wheat–rice cropping systems (Wu et al. 2015).

Discussion

Modifications of SRI concepts and their application will continue to be made in order to adapt to local environments; but that is part of the SRI approach to improving crop production. It is not a 'technology' in the sense that we understand from the Green Revolution; it is not a matter of relying primarily on improved genetic potential, because we see that available rice genomes have considerably more potential than is being exploited with currently–employed, sub–optimal management practices (Jiang et al. 2007). Further improvements in genetic potential can and should be made, but meeting future food needs is a larger task than should be placed just on the shoulders of plant breeders. Nor are production increases something to be achieved by relying heavily on the application of more and new external inputs, with their economic and environmental costs; SRI practices seek to reduce these costs. SRI experience and the agronomic and microbiological theorizing that helps explain the factor–productivity gains under SRI management point toward a different framework for agricultural R&D.

This body of theory and practice is still evolving, however. It has been seen in China and elsewhere that when the soil is (or becomes) more fertile, higher paddy yields can be obtained by a *lowering* of plant populations, in conjunction with other recommended practices (Toriyama and Ando 2011). This is counter–intuitive, but it is supported by SRI theory and results. On the other hand, farmers who grow double–season rice or a rice crop in rotation with another crop such as wheat, rapeseed or vegetables have seen that they can raise their yields by increasing their rice plant population in the second season, to compensate for its lower heat resources (Wu et al. 2013, 2015). This runs counter to the standard SRI recommendation, as does the use of seedlings that are older than recommended for SRI.

These alterations in practice may appear to contradict SRI principles, but it should be kept in mind that SRI is not a conventional technology. Rather it is an assemblage of practices based on certain ideas and insights that come from experience and observation, explainable by basic agronomic principles and validated by scientific methods. The aim of SRI is to serve better the needs of plants, and of the soil systems in which they grow, so that these can in turn better serve human needs. Increasing the plant population to accommodate a cooler temperature regime, in the example above, represents an appropriate agronomic practice rather than a negation of SRI principles.

With the high yields being attained and reported, the question is often raised whether these practices will 'exhaust' the soil unless large amounts of inorganic nutrients are supplied. This is an empirical matter. Thus far, soil evaluations have often shown improvement rather than depletion of soil nutrient stocks, provided that organic matter is provided to the soil systems rather than rely mostly on inorganic nutrient amendments (Ma et al. 2003; Gopalakrishnan et al. 2014; Wu and Ma 2015). But this is an important and complicated subject on which more research is needed. If nutrient constraints due to depletion are encountered, supplementation is possible and acceptable since SRI as we understand it is not an organic methodology on doctrinal grounds. Rather it is pragmatically organic to the extent that farmers' goals and needs (and societal objectives and interests such as environmental conservation and quality) can be served without reliance on inorganic sources of nutrients and crop protection (Anas et al. 2011).

In situations where there is need for macro– and particularly micronutrient soil amendments, some chemical fertilizer can be used with other SRI methods; and similarly in situations where crops' natural defenses with SRI management are not sufficient, agrochemical crop protection may be needed. Or some optimization among organic and inorganic sources may be beneficial for farmers and their farming, e.g., with integrated pest management or with integrated nutrient management (Lin et al. 2011; Wu and Ma 2015). SRI understanding places a 'burden of proof' on the use of external inputs whereas current agricultural theory and advice lays this burden upon alternative practices, taking agrochemical use as an unquestioned norm. SRI thinking gives attention and weight to what are now too often ignored or dismissed as externalities, or that are not considered because they are future effects, despite endorsements of sustainability as a criterion for policy and farmer decision–making. SRI is an 'organic' methodology in the sense that it appreciates and seeks to enhance the life in soil systems, and purposefully undertakes to benefit from this.

SRI improvements in crop performance have been seen in over 50 countries, such as India, Bangladesh, Indonesia, Kenya, Myanmar, Pakistan, and Thailand. Researchers have reported significant but wide–ranging gains in yield from SRI management methods (Kabir and Uphoff 2007; Sato and Uphoff 2007; Sinha and Talati 2007; Latif et al. 2009; Mishra and Salokhe 2011; Dass and Chandra 2013; Gehring et al. 2013; Ndiiri et al. 2013; Takahashi and Barrett 2014). Yield results have varied considerably from country to country and within countries, however, which raises valid concerns among agronomists. Variation has been considerably greater elsewhere than in China, where yields are already at a higher level than in most other countries and where there is thus less biological scope for variation.

The wide range of variation seen in SRI results has been a source for some of the skepticism that has beset SRI from the beginning. If SRI results were attributable to a particular improved genetic potential or to the input of chemical fertilizers, one could expect to have more predictability, less variability, or at least some evident proportionality in results. Given the current state of knowledge about SRI, we suggest that the variability in crop performance under SRI management derives from its being more biologically–driven than chemically–induced, and from the *expression* of genetic potential rather than from that potential itself as a fixed, static capacity.

Soil organisms ranging from microbes to earthworms, if abundant, active and biodiverse, are capable of mobilizing and making available nutrients within existing soil systems (fixing N, solubilizing P, cycling micronutrients) and providing various services, such as protection against pathogens, producing phytohormones, and inducing systemic resistance to diseases. They can even affect rice plants' expression of their genetic potential (Chi et al. 2005, 2010). We are only starting to understand the benefits that plants can get from being inhabited by symbiotic microbial endophytes (Uphoff et al. 2013), but these benefits parallel the observed effects that SRI practices have been documented to have on plants' morphology and physiology (Thakur et al. 2010a). Much as medical science is currently advancing rapidly through its investigations of what is called the human microbiome, SRI is tapping into the emerging body of biological science that addresses the plant–soil microbiome (Turner et al. 2014). That SRI methods consistently affect (improve) rice plants' expression of their genetic potential also offers opportunities for epigenetic research.

It should not be surprising that SRI results show considerable variance since they are driven more by endogenous processes within plant–soil–microbial ecosystems than by exogenous interventions. When all of the biological elements supporting SRI crop growth and health are in place and in synchronization, some remarkable yield gains are possible. Such yields have been controversial; however, they have been measured with standard, unbiased methods (Diwakar et al. 2012). Super–yields are, by definition, outliers, but they show the performance potential that exists within rice plants, and within the soil systems in which they grow, when conditions for growth are favorably optimized (Nemoto et al. 1995). It is averages, however, rather than outliers that improve people's living standards and sustain both their growth and health, so accordingly it is averages that should receive the most attention, and which have been our concern here.

Recently, a milestone project involving agronomists from 18 agricultural universities and institutes in China led by the China Agricultural University has addressed the benefits of what they call integrated soil–crop system management (ISSM) for rice, wheat and maize production in China (Zhang et al. 2012; Chen et al. 2014). ISSM practices also favor the appropriate crop management practices as in SRI, such as optimum planting density, sowing dates, and water-saving irrigation strategies (Zhang et al. 2012). ISSM with lower plant density and early sowing/transplanting dates generally produce higher yields compared with current practice in Wuxue County, Hubei province (personal communication with Huang Jianliang, Huazhong Agricultural University, one of the researchers who conducted the ISSM evaluations).

Another aspect of ISSM is that it also favors more rational N rates: reducing the N-fertilizer input along with the use of more organic fertilizer, described as "integrated nutrient management" (Zhang et al. 2012; Wu et al. 2015). This can go along with achieving a more grain yield and higher WUE, reducing irrigation, usually through alternate wetting and drying, which is similar concept of SRI, increasingly practiced in China (Yao et al. 2012). Thus, ISSM practices like lower planting density, earlier transplanting dates, cutting back on N-fertilizer, and reducing irrigation, all similar to SRI's main concepts, are becoming popular in some specific locations or provinces.

Conclusions

This review is an interim report on SRI as it is an evolving phenomenon, still a work in progress. The meta-analysis of multiple trials across many parts of China over the last decade showed that SRI methods are likely to raise rice yields by more than 10 % over current improved practices, with other benefits as well. The methods can reduce field requirements for irrigation water and seed, which will lower farmers' costs of production and increase their net income by more than their increase in paddy yield. Other benefits include greater resistance to pests and diseases, more tolerance of drought and other abiotic stresses, higher N use efficiency as well as water use efficiency, enhanced photosynthetic rates, and improved physiological traits.

Technological innovations such as the mechanization of transplanting and weeding or direct–seeding technology and other labor–saving strategies are likely to boost the diffusion of SRI within China and in other countries, enabling farmers to exploit more fully the advantages of relationships among plants, soil, water, nutrients, soil organisms and people that are illuminated by SRI ideas and experience. With diffusion, adoption and adaptation on a larger scale, SRI shows potential for buffering farmers and crops from some of the hazards of anticipated climate change and even for mitigating greenhouse–gas drivers for accelerating global warming. How much SRI ideas and practices can contribute to more environmentally–robust strategies for sustainable agriculture in China and the rest of the world is not known. But there is no reason why agricultural researchers, government decision–makers, and especially farmers should not take this agroecological innovation seriously, trying to understand it better and to utilize its opportunities beneficially.

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References

Abraham B, Araya H, Berhe T, Edwards S, Gujja B, Khadka R, Koma Y, Sen D, Sharif A, Styger E, Uphoff N, Verma A (2014) The system of crop intensification: reports from the field on improving agricultural production, food security, and resilience to climate change for multiple crops. Agric Food Secur 3:4, http://www.agricultureandfoodsecurity.com/content/3/1/4

Ainsworth EA, Davey PA, Bernacchi CJ, Dermody OC, Heaton EA, Moore DJ, Morgan B, Naidu SL, Ra HY, Zhu X, Curtis PS, Long SP (2002) A meta–analysis of elevated [CO_2] effects on soybean (*Glycine max*) physiology, growth and yield. Global Chang Biol 8:695–709

Anas I, Rupela O, Thiyagarajan T, Uphoff N (2011) A review of studies on SRI effects on beneficial organisms in rice soil rhizospheres. Paddy Water Environ 9:53–64

Barah BC (2009) Economic and ecological benefits of System of Rice Intensification (SRI) in Tamil Nadu. Agric Econ Res Rev 22:209–214

Barison J, Uphoff N (2010) Rice yield and its relation to root growth and nutrient–use efficiency under SRI and conventional cultivation: an evaluation in Madagascar. Paddy Water Environ 9:3–11

Belder P, Spiertz JHJ, Bouman BAM, Lu G, Tuong TP (2005) Nitrogen economy and water productivity of lowland rice under water–saving irrigation. Field Crop Res 93:169–185

Bouman BAM, Tuong TP (2001) Field water management to save water and increase its productivity in irrigated rice. Agric Water Manag 49:11–30

Bruinsma J (2009) The resource outlook to 2050: by how much do land, water, and crop yields need to increase by 2050? In: Bruinsma J (ed) Expert meeting on how to feed the world in 2050. FAO, Rome (www.fao.org/fileadmin/templates/)

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

Chen H, Zhu D, Wu L, Lin X, Zhang Y (2007) Effect of different fertilizer–N management on nitrogen use efficiency of rice and soil microorganism under SRI. China J Soil Sci 38:687–692, in Chinese with English abstract

Chen S, Zheng X, Wang D, Xu C, Zhang X (2013) Influence of the improved system of rice intensification (SRI) on rice yield, yield components and tillering characteristics under different rice establishment methods. Plant Prod Sci 16:191–198

Chen XP, Cui ZL, Fan MS, Vitousek P, Zhao M, Ma WQ, Wang ZL, Zhang WJ, Yan XY, Yang JC, Deng XP, Gao Q, Zhang Q, Guo SW, Ren J, Li SQ, Ye YL, Wang ZH, Huang JL, Tang QY, Sun YX, Peng XL, Zhang JW, He MR, Zhu YJ, Xue JQ, Wang GL, Wu L, An N, Wu LQ, Ma L, Zhang WF, Zhang FS (2014) Producing more grain with lower environmental costs. Nature 514:486–489

Chi F, Shen SH, Cheng HP, Jing YX, 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. J Appl Environ Microbiol 71:7271–7278

Chi F, Yan PF, Han F, Shen XY, Shen SH (2010) Proteomic analysis of rice seedlings infected by *Sinorhizobium meliloti* 1021. Proteomics 10:1861–1874

Curtis PS, Wang X (1998) A meta–analysis of elevated CO2 effects on woody plant mass, form, and physiology. Oecologia 113:299–313

Dass A, Chandra S (2013) Irrigation, spacing and cultivar effects on net photosynthetic rate, dry matter partitioning of rice under system of rice intensification in Mollisols of Northern India. Exp Agric 49:504–523

Deb D, Laessig J, Kloft M (2012) A critical assessment of the importance of seedling age in the system of rice intensification (SRI) in eastern India. Exp Agric 48:326–346

Diwakar MC, Kumar A, Verma A, Uphoff N (2012) Report on the world–record SRI yields in kharif season 2011 in Nalanda District, Bihar State, India. Agric Today, New Delhi 15:54–56

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

Fang Z, Styger E (2014) System of rice intensification in China: research dynamics and innovative adaptations. Presentation made at 4th Intl. Rice Congress, Bangkok, Oct 28–31. http://www.slideshare.net/SRI.CORNELL/1423–system–of–rice–intensification–in–china

Feng ZZ, Kobayashi K, Ainsworth EA (2008) Impact of elevated ozone concentration on growth, physiology, and yield of wheat (*Triticumaestivum L.*): a meta–analysis. Global Chang Biol 14:2696–2708

Gehring C, de Moura E, Soares R, Aguiar A, De Sousa A, Boddey R (2013) Ecological intensification of rice production in the lowlands of Amazonia–options for smallholder rice producers. Eur J Agron 46:25–33

Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, Pretty J, Robinson S, Thomas SM, Toulmin C (2010) Food security: the challenge of feeding 9 billion people. Science 327:812–818

Gopalakrishnan S, Kumar R, Humayun P, Srinivas V, Kumari B, Vijayabharathi R, Singh A, Surekha K, Padmavathi C, Somashekar N, Rao P, Latha P, Rao L, Babu V, Viraktamath B, Goud V, Loganandhan N, Gujja B, Rupela O (2014) Assessment of different methods of rice (*Oryza sativa*. L) cultivation affecting growth parameters, soil chemical, biological, and microbiological properties, water saving, and grain yield in rice–rice system. Paddy Water Environ 12:79–87

He Y, Jian F, Ou S, Huang S, Lin L, Cen Y (2004a) Trial system of rice intensification (SRI) and its prospect in Guangxi. Guangxi Agric Sci 35:362–364, in Chinese with English abstract

He Y, Ma J, Wei W (2004b) Effect of different kinds of fertilizers on the yield and grain quality in the SRI. Chin Agric Sci Bull 20:177–181, in Chinese with English abstract

Hedges LV, Gurevitch J, Curtis PS (1999) The meta–analysis of response ratios in experimental ecology. Ecology 80:1150–1156

Huang M, Zou Y, Feng Y, Cheng Z, Mo Y, Ibrahim M, Xia B, Jiang P (2011) No–tillage and direct seeding for super hybrid rice production in rice–oilseed rape cropping system. Eur J Agron 34:278–286

IRIN (2012) Analysis: why rice intensification matters in Asia. U.N. Office for the Coordination of Humanitarian Affairs, Bangkok, http://www.irinnews.org/report/95342/analysis–why–rice–intensification–matters–in–asia

Iswandi A, Utari NA, Sukmasakti YV, Widyastuti R (2014) Rice ratooning with high yield is possible, poster presented at 4th International Rice Congress, Bangkok, October 27–31

IWMI (2007) Rice: feeding the billions. In Water for food, water for life: a comprehensive assessment of water management in agriculture, Chapter 14 Earthscan, London, and International Water Management Institute, Colombo. (http://www.iwmi.cgiar.org/Assessment/)

Jagannath P, Pullabhotla H, Uphoff N (2013) Meta–analysis evaluating water use, water saving and water productivity in irrigated production of rice with SRI vs. standard management methods. Taiwan Water Conserv 61:14–49, in English with Chinese abstract

Jiang H, Guo L, Qian Q (2007) Recent progress on rice genetics in China. J Integr Plant Biol 49:776–790

Jin X, Jin Z, Sun T, Shang W, Li D, Xu F (2005) Summaries in the study of 3–S cultivating technique of rice in cold zone. Chin Agric Sci Bull 21:136–141, in Chinese with English abstract

Kabir H, Uphoff N (2007) Results of disseminating the system of rice intensification with farmer field school methods in Northern Myanmar. Exp Agric 43:464–476

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

Lal R (2004) Carbon from farm operations. Environ Int 30:981–990

Latif MA, Ali MY, Islam MR, Badshah MA, Hasan MS (2009) Evaluation of management principles and performance of the system of rice intensification (SRI) in Bangladesh. Field Crop Res 114:255–262

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

Lin H, Wu S, Wu C, Li X, Liao C, Chen A (2005a) Agronomic performance of system for rice intensification under single late–season rice. Crops J 1:36–37, in Chinese with English abstract

Lin XQ, Zhou W, Zhu DF, Zhang Y (2005b) Effect of SWD irrigation on photosynthesis and grain yield of rice (*Oryza sativa* L.). Field Crop Res 94:67–75

Lin H, Wu C, Lai L (2008) The primary effects of system for rice intensification on conventional early Indica rice. China Rice 5:56–58, in Chinese with English abstract

Lin XQ, Zhu DF, Chen H, Cheng SH, Uphoff N (2009) Effect of plant density and nitrogen fertilizer rates on grain yield and nitrogen uptake of hybrid rice (*Oryza Sativa* L.). J Agric Biotechnol Sust Dev 1:44–53

Lin XQ, Zhu DF, Lin X (2011) Effects of water management and organic fertilization with SRI crop practices on hybrid rice performance and rhizosphere dynamics. Paddy Water Environ 9:33–39

Lu S, Dong Y, Yuan J, Lee H, Padilla H (2013) A high–yielding, water–saving innovation combining SRI with plastic cover on no–till raised beds in Sichuan, China. Taiwan Water Conserv 61:94–109, in English with Chinese abstract

Ma BL, Ying J, Dwyer LM, Gregorich EG, Morrison MJ (2003) Crop rotation and soil nitrogen amendment effects on maize production in Eastern Canada. Can J Soil Sci 83:483–495

Mati B, Wanjogu R, Odongo B (2011) Introduction of the system of rice intensification in Kenya: experiences from Mwea irrigation scheme. Paddy Water Environ 9:145–154

Mishra A, Salokhe V (2011) Rice root growth and physiological responses to SRI water management and implications for crop productivity. Paddy Water Environ 9:45–52

Mishra A, Whitten M, Ketelaar JW, Salokhe VM (2007) The system of rice intensification (SRI): a challenge for science, and an opportunity for farmer empowerment towards sustainable agriculture. Int J Agric Sustain 4:193–212

Mueller N, Gerber J, Johnston M, Ray D, Ramankutty N, Foley J (2012) Closing yield gaps through nutrient and water management. Nature 490:254–257

Ndiiri J, Mati B, Home P, Odongo B, Uphoff N (2013) Adoption, constraints and economic returns of paddy rice under the system of rice intensification in Mwea, Kenya. Agric Water Manag 129:44–55

Nemoto K, Morita S, Baba T (1995) Shoot and root development in rice related to the phyllochron. Crop Sci 35(1):24–29

Noltze M, Schwarze S, Qaim M (2012) Understanding the adoption of system technologies in smallholder agriculture: the system of rice intensification (SRI) in Timor Leste. Agric Syst 108:64–73

Peng S, Huang J, Sheehy J, Laza R, Visperas R, Zhong X, Centeno G, Khush G, Cassman K (2004) Rice yield declines with higher night temperature from global warming. Proc Natl Acad Sci U S A 101:9971–9975

Peng S, Tang Q, Zou Y (2009) Current status and challenges of rice production in China. Plant Prod Sci 12:3–8

Plabita R, Raj RK (2014) Extent of adoption of practices under system of rice intensification in Odisha. Oryza 51:81–85

Rabenandrasana J (1998) Revolution in rice intensification in Madagascar. LEISA Magazine 15(3/4):48–49

Reddy K, Sreenivasulu S, Manohar C (2012) A report on direct–seeding technology with SRI concepts in rice using drum seeder in Chittoor district of Andhra Pradesh, India. Acharya Ranga Krishi Vigyan Kendra, Tirupati, AP, India (http://ciifad.cornell.edu/sri/countries/india/AP/InAPDrumSeeder_KVKBalaReddy09.pdf)

Rosenberg MS, Adams DC, Gurevitch J (2000) Metawin: statistical software for meta–analysis, version 2.1. Sinauer Associates, Inc, Sunderland

Santos A, Fageria N, Prabhu A (2003) Rice ratooning management practices for higher yields. Commun Soil Sci Plant Anal 34:881–918

Sato S, Uphoff N (2007) A review of on–farm evaluations of system of rice intensification (SRI) methods in eastern Indonesia. CAB Rev 2:54

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

Setiawan BI, Imansyah A, Arif C, Watanabe T, Mizoguchi M, Kato H (2014) SRI paddy growth and GHG emissions at various groundwater levels. Irrig Drain 63:612–620

Sharif A (2011) Technical adaptations for mechanized SRI production to achieve water saving and increased profitability in Punjab, Pakistan. Paddy Water Environ 9:111–119

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 Crop Res 88:1–8

Sinha SK, Talati J (2007) Productivity impacts of the system of rice intensification (SRI): a case study in West Bengal, India. Agric Water Manag 87:55–60

Stoop WA (2011) The scientific case for system of rice intensification and its relevance for sustainable crop intensification. Int J Agric Sustain 9:443–455

Stoop WA, Uphoff N, Kassam AH (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

Takahashi K, Barrett C (2014) The System of Rice Intensification and its impacts on household income and child schooling: Evidence from rural Indonesia. Amer J Agric Econ 96:269–289

Tao L, Wang X, Min SK (2002) Physiological effects of SRI methods in the rice plant. In: Uphoff N, Fernandes ECM, Yuan LP, Peng JM, Rafaralahy R, Rabenandrasana J (eds) Assessments of the system of rice intensification (SRI): Proceedings of an international conference, Sanya, China, April 1–4, 2002. CIIFAD, Ithaca, pp 132–136, http://sri.ciifad.cornell.edu/proc1/sri_29.pdf

Thakur AK, Uphoff N, Antony E (2010a) An assessment of physiological effects of system of rice intensification (SRI) practices compared to recommended rice cultivation practices in India. Exp Agric 46:77–98

Thakur AK, Rath S, Roychowdhury S, Uphoff N (2010b) Comparative performance of rice with system of rice intensification (SRI) and conventional management using different plant spacings. J Agron Crop Sci 196:146–159

Tilman D, Cassman KG, Matson PA, Naylor R, Polasky S (2002) Agricultural sustainability and intensive production systems. Nature 418:671–677

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

Turner TR, James EK, Poole PS (2014) The plant microbiome. Genome Biol 14:209. doi:10.1186/gb-2013-14-6-209

Uphoff N (1999) Agroecological implications of the system of rice intensification (SRI) in Madagascar. Environ Dev Sustain 1:297–313

Uphoff N (2003) Higher yields with fewer external input? The System of Rice Intensification and potential contributions to agricultural sustainability. Int J Agric Sustain 1:38–50

Uphoff N (2012) Supporting food security in the 21st century through resource-conserving increases in agricultural production. Agric Food Secur 1:18

Uphoff N, Randriamiharisoa R (2002) Possibilities for reducing water use in irrigated rice production through the Madagascar system of rice intensification (SRI). In: Bouman BA et al (eds) Water–wise rice production. Intl. Rice Research Institute, Los Baños, pp 71–87

Uphoff N, Ball A, Fernandes ECM, Herren H, Husson O, Laing M, Palm CA, Pretty J, Sanchez PA, Sanginga N, Thies JE (eds) (2006) Biological approaches to sustainable soil systems. CRC Press, Boca Raton

Uphoff N, Kassam A, Harwood R (2011) SRI as a methodology for raising crop and water productivity: productive adaptations in rice agronomy and irrigation water management. Paddy Water Environ 9:3–11

Uphoff N, Chi F, Dazzo FB, Rodriguez RJ (2013) Soil fertility as a contingent rather than inherent characteristic: considering the contributions of crop–symbiotic soil biota. In: Lal R, Stewart B (eds) Principles of sustainable soil management in agroecosystems. Taylor & Francis, Boca Raton, pp 141–166

Wang S, Cao W, Jiang D, Tai D, Zhu Y (2003) Effects of SRI technique on physiological characteristics and population

development in rice. Chin J Rice Sci 17:31–36, in Chinese with English abstract
Wu S (2007) The contrastive experiments under system for rice intensification. Inn Mong Agric Sci Technol 33:41–42, in Chinese with English abstract
Wu W, Ma B (2015) Integrated nutrient management (INM) for sustaining crop productivity and reducing environmental impact: a review. Sci Total Environ 512:415–427
Wu W, Nie L, Liao Y, Shah F, Cui K, Wang Q, Huang J (2013) Towards yield improvement of early season rice: other options under double rice–cropping system in central China. Eur J Agron 45:75–86
Wu W, Huang J, Shah F, Uphoff N (2015). Evaluation of system of rice intensification methods applied in the double rice–cropping system in central China. Adv. Agron. 132. doi: 10.1016/bs.agron.2015.01.002
Xiong H, Ran M, Xu F, Hong S (2000) Achievements and developments of ratooning rice in south of China. Acta Agron Sin 26:297–304, in Chinese with English abstract
Xu F, Ma J, Wang H, Liu H, Huang Q, Ma W, Ming D (2003) The characteristics of roots and their relation to the formation of grain yield under the cultivation by system of rice intensification (SRI). Hybrid Rice 18:61–65, in Chinese with English abstract
Xu F, Ma J, Wang H, Liu H, Huang Q, Ma W, Ming D (2005) Rice quality under the cultivation of SRI. Acta Agron Sin 31:577–582, in Chinese with English abstract
Xu X, Li XY, Li H (2006) Socio–economic impact analysis of SRI in China. China Rural Econ. March, in Chinese; English version available at: http://sri.ciifad.cornell.edu/countries/china/cnciadeng.pdf
Xu X, Liu Y, Shi Y, Laura P (2013) Discourse analysis of the plight of the extension of the new style modern agricultural technology—Take the extension of the system of rice intensification (SRI) in Y village, Sichuan province as an example. J China Agric Univ 1:1–8, in Chinese with English abstract
Yan X, Akiyama H, Yagi K, Akimoto H (2009) Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines. Global Biogeochem Cycles 23, GB2002. doi:10.1029/2008GB003299
Yan G, Zheng X, Cui F, Yao Z, Zhou Z, Deng J, Xu Y (2013) Two–year simultaneous records of N_2O and NO flues from a farmed cropland in the northern China plain with a reduced nitrogen addition rate by one–third. Agric Ecosyst Environ 178:39–50
Yao F, Huang J, Cui K, Nie L, Xiang J, Liu X, Wu W, Chen M, Peng S (2012) Agronomic performance of high-yielding rice variety grown under alternate wetting and drying irrigation. Field Crops Res 126:16–22
Yuan LP (2001) The system of rice intensification. Hybrid Rice 16:1–3, in Chinese with English abstract
Yuan LP (2002) A scientist's perspective on experiences with SRI in China for raising yields of super–hybrid rice. In: Uphoff N, Fernandes ECM, Yuan LP, Peng JM, Rafaralahy R, Rabandrasana J (eds) Assessments of the system of rice intensification (SRI): proceedings of an international conference, Sanya, China, April 1–4, 2002. CIIFAD, Ithaca, http://sri.ciifad.cornell.edu/proc1/sri_06.pdf
Zhang WJ, Lu M (2010) Innovative rice–wheat cropping system for higher yield with lower emissions in China, based on concepts of SRI. Report for Institute of Crop Science, China Academy of Agricultural Sciences, Beijing. (http://sri.ciifad.cornell.edu/countries/china/ChinaSWRI_Zhang2010.pdf)
Zhang F, Cui Z, Chen X, Ju X, Shen J, Chen Q, Liu X, Zhang W, Mi G, Fan M, Jiang R (2012) Integrated nutrient management for food security and environmental quality in China. Adv Agric 116:1–40
Zhao L, Wu L, Li Y, Lu X, Zhu D, Uphoff N (2009a) Influence of the System of Rice Intensification on rice yield and nitrogen and water use efficiency with different N application rates. Exp Agric 45:275–286
Zhao L, Wu L, Li Y, Wu M (2009b) Effects of the system of rice intensification on soil biological properties. Acta Pedologica Sin 46:321–325, in Chinese with English abstract
Zhao L, Wu L, Li Y, Animesh S, Zhu D, Uphoff N (2010) Comparisons of yield, water use efficiency, and soil microbial biomass as affected by the System of Rice Intensification. Commun Soil Sci Plant Anal 41:1–12
Zhao L, Wu L, Wu M, Li Y (2011) Nutrient uptake and water use efficiency as affected by modified rice cultivation methods with reduced irrigation. Paddy Water Environ 9:25–32
Zheng JG, Lu XJ, Jiang XL, Li CD (2004) Testing modifications for the system of rice intensification (SRI) to achieve super–high yield in the Sichuan basin. Southwest China J Agric Sci 17:169–173, in Chinese with English abstract
Zheng JG, Chi Z, Li X, Jiang X (2013) Agricultural water savings possible through SRI for water management in Sichuan, China. Taiwan Water Conserv 61:50–62, in English with Chinese abstract
Zhu DF (2004) Development of system of rice intensification for rice production in China. Presentation at World Rice Research Congress, Tsukuba, Japan, Nov. 7. (http://www.slideshare.net/SRI.CORNELL/0429–development–of–system–of–rice–intensification–for–rice–production–in–china)
Zhu DF (ed) (2006) The theory and practice of SRI. Chinese Press of Science and Technology for Agriculture, Beijing, in Chinese
Zhu H, Chen H (2006) Research of ratooning rice and its prospects in Fujian province. Subtrop Agric Res 2:170–175, in Chinese with English abstract
Zhu DF, Cheng SH, Zhang YP, Lin XQ (2002) Tillering patterns and the contribution of tillers to grain yield with hybrid rice and wide spacing. In: Uphoff N, Fernandes ECM, Yuan LP, Peng JM, Rafaralahy R, Rabenandrasana J (eds) Assessments of the system of rice intensification (SRI): proceedings of an international conference, Sanya, China, April 1–4, 2002. CIIFAD, Ithaca, pp 125–131, http://sri.ciifad.cornell.edu/proc1/sri_28.pdf
Zhu Y, Xiong H, Xu F, Guo X, Zhang L (2011) Research on system of rice intensification (SRI) technology in China. Agric Sci Technol 12:1818–1825