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ARTICLE

Nutrient uptake and water use efficiency as affected by modified rice cultivation methods with reduced irrigation

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Abstract A field experiment was conducted in 2005 to investigate the effects of modified rice cultivation methods on: water use efficiency, the uptake of nutrients (N, P and K) by plants, and their distribution within plants and their internal use efficiency. The treatments were modified methods of irrigation, transplanting, weeding, and nutrient management, comparing the System of Rice Intensification (SRI) with standard rice-growing methods including traditional flooding (TF). Results showed that the uptake of N, P, and K by rice plants during their growth stages was greater with SRI management compared to TF, except during the tillering stage. At maturity stage, SRI plants had taken up more nutrients in their different major organs (leaves, stems, and sheaths; panicle axis; and seeds), and they translocated greater amount of nutrients to the grain. Under SRI, the ratio of N, P, and K in seed grain to total plant N, P, and K was 4.97, 2.00, and 3.01% higher, respectively, than with TF. Moreover, under SRI management, internal use efficiency of the three macronutrients (N, P, and K) was increased by 21.89, 19.34, and 16.96%, respectively, compared to rice plants under TF management. These measurements calibrate the crop's physiological response to differences in cultural practices, including the maintenance of aerobic versus anaerobic environment in the root zones. With SRI, irrigation water applications were reduced by 25.6% compared to TF. Also, total water use efficiency and irrigation water use efficiency was increased with SRI by 54.2 and 90.0%, respectively. Thus, SRI offered significantly greater water saving while at the same time producing more grain yield, in these trials 11.5% more compared to TF.

Keywords System of rice intensification · Nutrient uptake · Internal use efficiency · Water use efficiency

Introduction

Rice is the world's most important food crop and a major food grain for more than a third of the world's population (Prasertsak and Fukai 1997). China's 31.7 million ha of rice fields, which account for about 20% of the world's rice area, produce about 35% of its total rice (FAO 2001). Rice production consumes large quantities of irrigation water, up to about 90% of the total water for all crops (Bhuiyan 1992). However, fresh water for irrigation is becoming scarce because of increasing competition from urban, industrial, and environmental demands (Guerra et al. 1998; Bouman and Tuong 2001; Tuong and Bouman 2003).

Water resource limitations threaten the sustainability of irrigated rice systems in many countries. Rice offers great

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potential to save irrigation water because its physiological water requirement (4500 m^3 water ha^{-1}) is much less than what is currently considered to be needed (Guerra et al. 1998; Si 2000). Furthermore, irrigation constraints crucially affect whether the rice sector can expand overall production enough to meet continually growing demand, since about 75% of the world's rice production comes from irrigated lowland rice fields (Maclean et al. 2002; Nguyen and Ferrero 2006). Water-saving rice cultivation methods that can offer greater water productivity are urgently needed to keep up with future food demands, while they are at the same time important for ensuring rice production systems' future viability.

A water-saving rice cultivation method known as the System of Rice Intensification (SRI) has been introduced into China from Madagascar. With SRI, rice productivity is reportedly increased by simultaneously modifying several agronomic and water management practices in rice cultivation (Stoop et al. 2002). Its changes in standard management practices include: transplanting very young seedlings at the 2–3 leaf stage; having just one seedling per hill with wider spacing in a square pattern rather than in rows; maintaining non-flooded soil conditions during the vegetative stage and very shallow irrigation after flowering; soil-aerating mechanical hand weeding; and application of large quantities of organic manure (Uphoff et al. 2002.

SRI alters the environment for growing rice with no standing water during the vegetative growth period, and only a thin layer of water on the field (1–2 cm) from panicle initiation until 10–15 days before harvest. These practices are likely to influence nutrient availability and forms, such as promoting populations of aerobic phosphorus-solubilizing microbes and providing more nitrogen in nitrate (NO_3) form rather than as ammonium (NH_4) when soil is kept aerobic rather than reduced (Kronzucker et al. 1999; Krouk et al. 2010). However, there is little research information about the effects of SRI practices on the nutrient uptake by rice plants and on their nutrient use efficiency. This study undertook to evaluate the effects of different rice cultivation methods on the uptake of N, P, and K and on use efficiency, with water management as a key variable and making evaluations of water use efficiency.

Materials and methods

Site description

Field experiments were conducted in 2005 on the farm of Zhejiang University, Huajia Chi campus, in Hangzhou (30°16′ N, 120°12′ E). The elevation is 4.3 m, and paddy soil at the experimental site (clay loamy typic-hapli-stagnic anthrosol) has a pH of 6.5; organic matter of 11.2 g kg^{-1}; available N of 71.9 mg kg^{-1}; Olsen-P of 45.0 mg kg^{-1}; and available K of 64.0 mg kg^{-1}. Data on temperature, rainfall and sunshine hours are shown in Fig. 1.

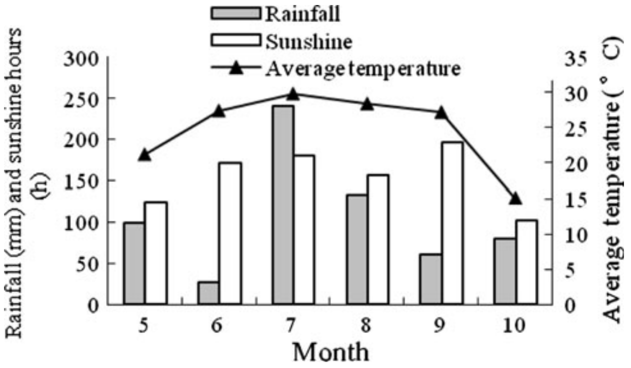

Fig. 1 Monthly average temperature, rainfall, and sunshine hours at experiment site

Experimental design, fertilization, and cultural practices

The experiment was a randomized complete block design with two treatments and three replications. The two main treatments were traditional flooding (TF) with standard crop management, and the SRI. All plots (5.5 × 4.2 m) were surrounded by consolidated bunds, lined with plastic sheets installed to a depth of 0.3 m to prevent seepage between plots. Land preparation for both TF and SRI was standard wet tillage and harrowing. The rice variety planted was Bing 98110, a japonica rice variety widely grown in the Yangtze River delta.

For the SRI treatments, 15-day-old seedlings were transplanted singly with spacing of 25 × 30 cm; and for TF, 30-day-old seedlings spaced 25 × 17 cm were transplanted, one per hill (an SRI practice). Plant populations m^{-2} were 13.3 and 23.5, respectively, the TF plots having 76.7% more plants. Transplanting was done on May 19, with harvesting on October 19.

Both treatments received 92 kg N ha^{-1} as urea, 54 kg P_2O_5 ha^{-1} as calcium phosphate, and 67.5 kg K_2O ha^{-1} as potassium chloride, applied as basal fertilization incorporated one day before transplanting. At tillering and booting stage, both treatments received 23 kg N ha^{-1}. Thus, the effects of differences in soil fertilization (SRI favors organic fertilization) were not evaluated in these trials.

TF plots were continuously flooded with 2–10 cm water depth except at the end of the growth cycle when plots were drained 7 days before harvest. SRI plots were kept saturated the first week after transplanting; thereafter, their soil was maintained in a moist condition without standing water covering the field until 15 days after panicle initiation; then a thin layer (2 cm) of water was maintained thereafter. Each main plot was irrigated separately, with water supplied every 3–7 days, depending on ambient temperature affecting evapotranspiration. Irrigation water was provided from a tap to a depth of 2 cm each time, as measured by a plastic ruler inserted into the plot. In SRI, manual weeding was done three times during the growing season, so the effects of the soil-aerating practice of mechanical weeding, recommended with SRI, were not evaluated either.

Sampling and nutrient analysis

Five randomly selected rice hills were sampled in each plot at tillering stage (June 19), jointing stage (July 25), booting stage (August 15), grain-filling stage (September 23), and post-harvest (October 17). The plants sampled on October 17 were separated into leaves, stems and sheaths, panicle axis, and grains. At maturity, grain yield was calculated as the mean from two 5 m^2 samples per plot. Such sampling is a common practice for estimating yields, e.g., Kato et al. (2009); Li et al. (2009), and should not have introduced any significant bias in comparing the two sets of treatments on an area basis.

The amount of aboveground biomass after the samples had been dried at 70°C was recorded as dry weight. The samples were then ground to pass through a 250-mesh sieve. The N in plant samples was determined by Kjeldahl method; P by colorimetric vanadate molybdenum yellow method; and K was determined using flame photometry after plant samples had been digested in hot H_2SO_4, using salicylic acid and H_2O_2 as additives. The uptake of N, P, and K was calculated by multiplying the concentration of each nutrient by the dry weight expressed in mg $plant^{-1}$. Internal nutrient efficiency (INE) (Peng et al. 2006) as kg kg^{-1} of N, P, and K was calculated by dividing grain yield by the total nutrient uptake.

Statistical analysis

Data were analyzed statistically by analysis of variance (ANOVA) method using Data Processing System (DPS) software. Average values were compared using the least significant difference (LSD) test at the 5% level (Tang and Feng 2002).

Results

Nutrient uptake by rice plants

SRI treatments significantly affected the uptake of N, P, and K by rice plants during their growth (Figs. 2a, 3a, 4a). Under TF, the respective uptakes of macronutrients ranged, from tillering to harvesting, from 39.14 to 628.29 mg N $plant^{-1}$, 16.29 to 293.19 mg P $plant^{-1}$, and 42.17 to 679.60mg K $plant^{-1}$. At the same time, with SRI practices macronutrient uptake ranged from 25.49 to 1105.08 mg N $plant^{-1}$, 9.64 to 526.65 mg P $plant^{-1}$, and 29.26 to 1245.52 mg K $plant^{-1}$ during the successive stages of growth.

SRI methods significantly increased total N, P, and K uptake by individual plants at the different growth stages (except at tillering stage) compared to TF. The amount of N, P, and K uptake by individual plants during the grain-filling stage (September 23) to maturity stage (October 17) was considerably higher under SRI management than with TF, being greater by 12.0, 16.9, and 2.5%, respectively.

On an area basis, however, reflecting differences in plant population, there was little difference in total above-ground plant N, P, and K between the SRI and TF treatments (Figs. 2b, 3b, 4b). Under SRI management, above-ground

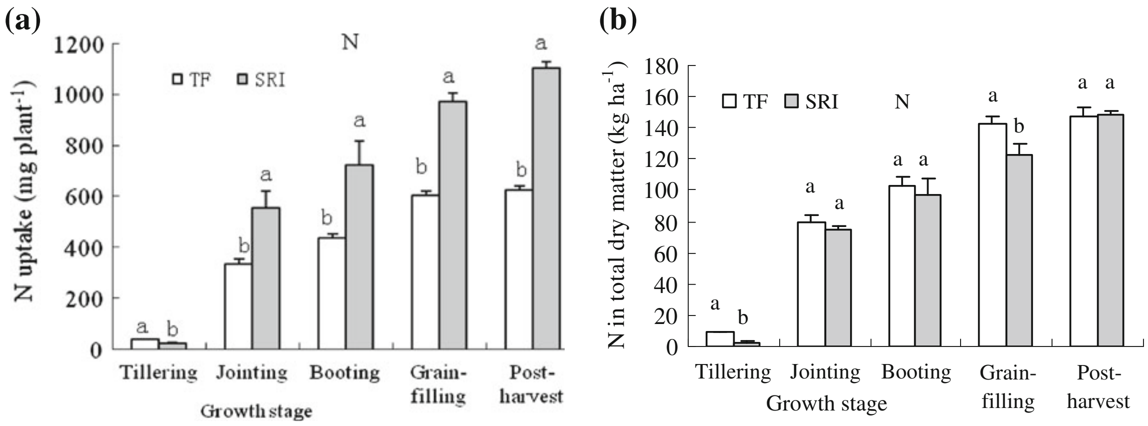

Fig. 2 N uptake by rice at different growth stages per plant and on area basis under traditional flooding versus SRI management

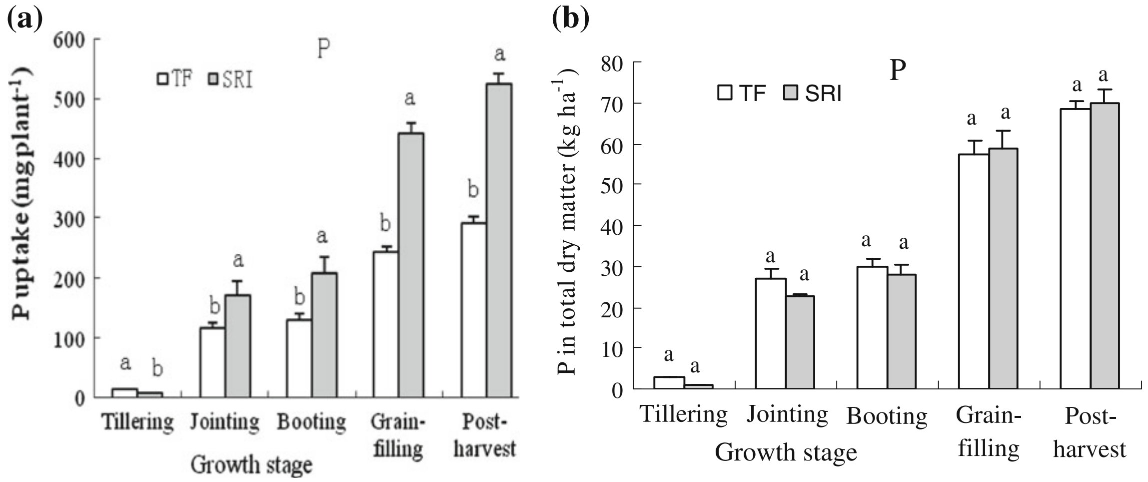

Fig. 3 P uptake by rice at different growth stages per plant and on area basis under traditional flooding versus SRI management

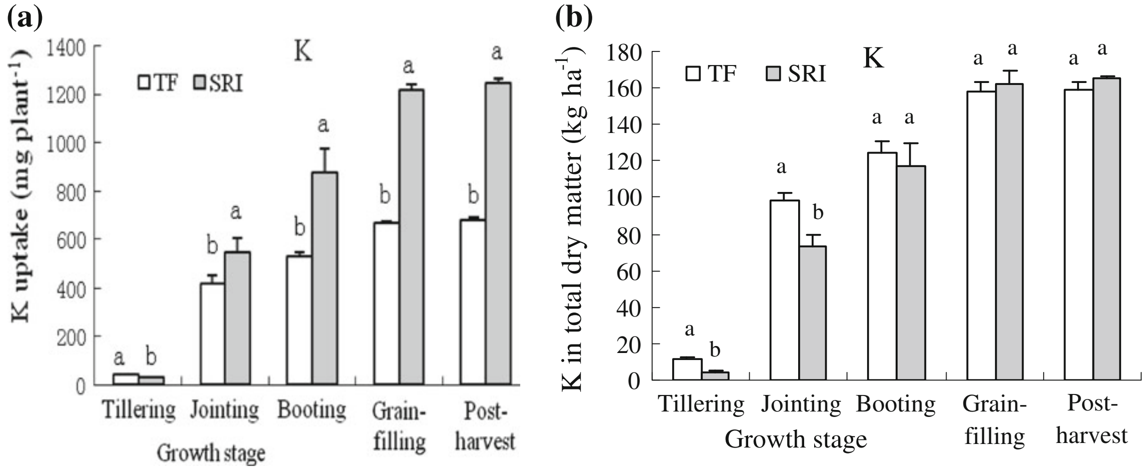

Fig. 4 K uptake by rice at different stages per plant and on area basis under traditional flooding versus SRI management

plant P and K tended to be lower than TF before the grain-filling stage, but then higher than TF once grain filling commenced. Above-ground plant N on an area basis tended to be lower for SRI than TF, although by the post-harvest stage, this amounts of N taken up had become equal.

Nutrient uptake and distribution in different organs

Uptake of N, P, and K by the leaves, stems and sheaths, panicle axis, and seed was higher under SRI than TF as seen in Figs. 5, 6 and 7. The ratios of N, P, and K in the leaves to total plant N, P, and K uptake were 6.72, 7.27, and 12.24%, respectively lower with SRI than TF. On the other hand, the ratios of N, P, and K in the stems and sheaths, panicle axis, and grain to total N, P and K uptake increased with SRI compared to TF (Figs. 5, 6, 7). With SRI management, the ratios of N, P, and K in the grain were 4.97, 2.00, and 3.0%, respectively, higher than with TF.

Grain yield and yield components

In these trials, total grains per panicle and percentage of filled-grains under SRI were slightly less than TF, but the difference was not significant (Table 1). There was no significant difference in 1000-grain weight under both treatments. Compared with TF, grain yield and effective panicles under SRI increased significantly by 11.5 and 20.3%, respectively.

Effects of SRI on water application and water use efficiency

During the rice-growing season, the total water consumption for SRI was 1297.7 mm, much less than that with TF, 1774.2 mm (Table 2). The irrigation water use in SRI was reduced by 25.6% compared to TF.

Fig. 5 N uptake and distribution among different organs at maturing stage

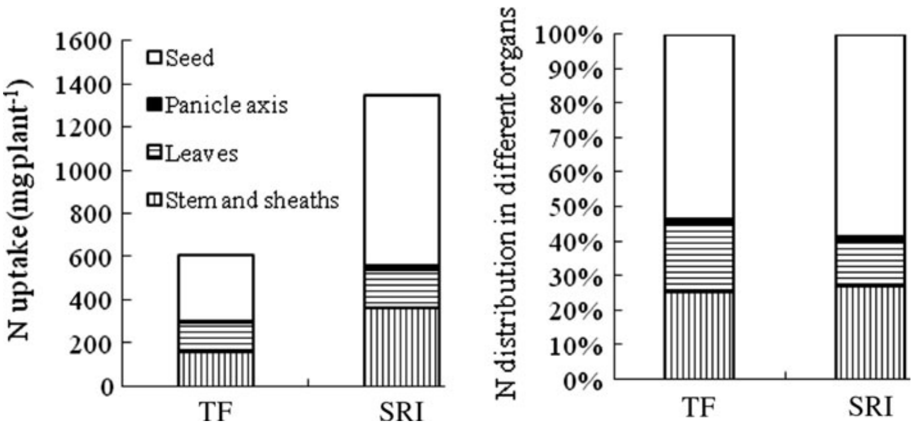

Fig. 6 P uptake and distribution among different organs at maturing stage

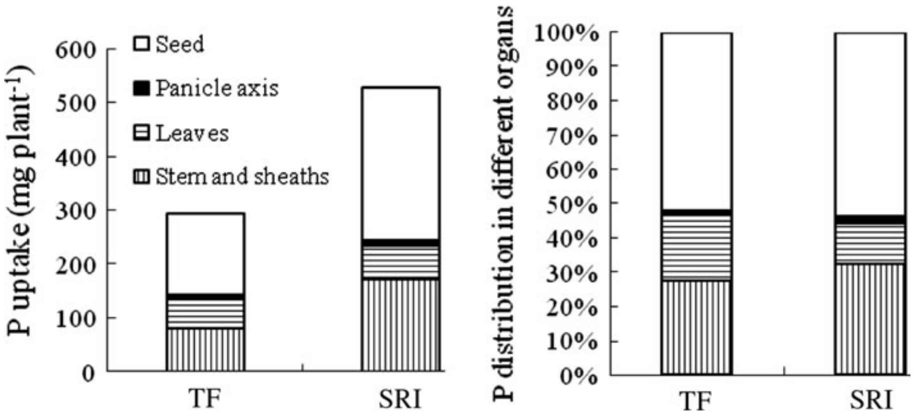

Fig. 7 K uptake and distribution among different organs at maturing stage

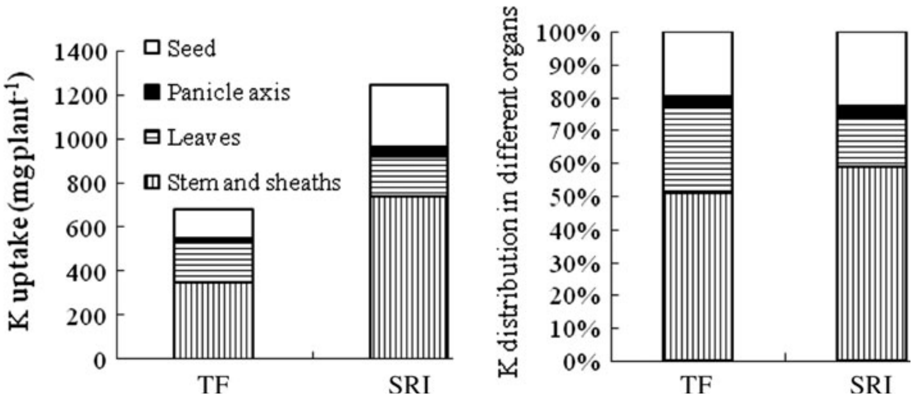

Table 1 Grain yield and yield components under SRI and traditional flooding (TF) ($n = 3$)

Treat- ment	Effective panicles ($\times 10^4$ ha^{-1})	Total grains panicle^{-1}	Filled grains (%)	1000-grain weight (g)	Yield (t ha^{-1})
SRI	215.9 a	175.4 a	79.5 a	24.2 a	6,610.0 a
TF	179.5 b	180.2 a	81.9 a	23.8 a	5,849.2 b

Data followed by the same letters are not significantly different at $P < 0.05$ level of significance

SRI System of Rice Intensification, *TF* traditional flooded rice cultivation

Table 2 Water consumption and water use efficiency under different cultivation systems

Treatment	Irrigation (mm)	Rainfall (mm)	Total (mm)	WUE	IWUE
TF	1175.2	599	1774.2	0.330 b	0.498 b
SRI	698.7	599	1297.7	0.509 a	0.946 a

Values followed by the same letter in a column are not significantly different at the 5% level by LSD

Overall water use efficiency (WUE) was calculated as grain yield per unit of total water consumption, while irrigation water use efficiency (IWUE) represents the grain yield per unit of irrigation water consumed. With SRI, it was seen that both WUE and IWUE were higher, by 54.2 and 90.0%, respectively, compared to TF. SRI management thus reduced water consumption while increasing WUE and IWUE significantly compared to TF.

Effects of SRI on nutrient use efficiency

Internal nutrient efficiency for the macronutrients N, P, and K was also calculated. This was found to be significantly greater under SRI, by 21.9, 19.3, and 17.0%, respectively, compared to TF (Table 3).

Discussion

In these experiments, SRI practices increased rice plants' nutrient uptake for N, P, and K and also improved the ratio of nutrients going into the grain. Above-ground nutrient accumulation on an area basis was slightly higher with SRI management than with TF, even though plant density was considerably lower with SRI than TF, in these trials with 44% fewer plants. Since the TF treatments in these trials were done also with single plants, like SRI, but more closely spaced, we note that possibly more or less difference would be observed with TF planting when done in clumps.

The internal use efficiency of N, P, and K was significantly increased in SRI-grown plants, by 21.89, 19.34, and 16.96%, respectively. Our results showed SRI methods to be more conducive for nutrient uptake by rice plants and also to promote the translocation of nutrients from leaves to the grain. Because the root is the main organ for nutrient uptake, the greater biomass of roots and their higher physiological activity under SRI practices (Xu et al. 2003; Satyanarayana 2005; Rupela et al. 2006) would beneficial for nutrient uptake. Rupela et al. (2006) found root mass, root density, and root volume to be all significantly higher with SRI cultivation than in flooded rice, as reported in Iswandi et al. (2011).

Table 3 Internal nutrient efficiency (INE) of N, P, and K under different cultivation systems

Treatment	Internal nutrient efficiency (INE, kg kg^{-1})		
	N	P	K
TF	40.75 b	87.32 b	37.67 b
SRI	49.67 a	104.21 a	44.06 a

Values followed by the same letter in a column are not significantly different at the 5% level by LSD

More nutrient uptake by rice with SRI management could be due in part to the transplantation of younger seedlings, which is seen to contribute to more prolific root growth. Mishra and Salokhe (2008) found that younger seedlings performed better than older seedlings when transplanted into either flooded or non-flooded soils, with greater uptake of nitrogen and manganese than older seedlings.

Continuously submergence of paddy fields significantly decreases rhizosphere soil redox potential and simultaneously enhances the concentration of extractable (free) Fe^{2+}, which is potentially toxic to rice plants, due to inhibiting root growth and impairing nutrient uptake (Olaleye et al. 2001; Sahrawat 2000; Yang et al. 2004). SRI plants have larger and longer-lived root systems because intermittent irrigation improves oxygen supply to root systems with associated advantages for nutrient uptake (Stoop et al. 2002).

Another explanation for increased nutrient uptake and translocation to grain, with more internal use efficiency of N, P, and K could be that SRI practices create a more beneficial soil environment for rice growing and nutrient uptake with optimization of air and water in the soil, these two elements being inversely correlated. Alternate wetting and drying throughout the crop cycle rather than continuously flooded condition may affect nutrient forms and availability as well as biological processes in the soil. Yang et al. (2005) reported that alternative wetting and drying soil increased microbial biomass compared with flooded conditions. Bonkowski (2004) has indicated that under more aerobic soil conditions, there will be larger populations of soil fauna that contribute to biological processes for supplying N needs of plants. Furthermore, it has been seen that higher microbial biomass C and N was obtained under SRI management than with TF (Rupela et al. 2006; Zhao et al. 2010).

SRI has been studied often since 2000 in different areas of China, evaluating the effects of plant density, rice variety, and forms and amounts of fertilizer (chemical and organic). Most often, this research has reported significant yield-increasing effects of SRI management with reductions in irrigation water (Chen et al. 2006; Liang et al.

2004; Lin et al. 2005, 2006; Long et al. 2005; Tao and Ma 2003; Wang et al. 2003; Xu et al. 2003; Yu et al. 2003, 2005; Yuan 2001; Zhong et al. 2003; Zhu 2006).

Moreover, we have been conducting our own field experiments on SRI for 3 years (2004–2006) and all of the trials showed that total water use efficiency and irrigation water use efficiency were significantly greater due to higher yields with a lesser amount of irrigation water than is required with the traditional flooded system (Zhao et al. 2009, 2010). SRI has shown consistent water-saving effect with higher grain yield.

However, it should be noted that SRI fields had to be irrigated more frequently than TF fields in our study, probably due to higher temperatures and evaporation during the rice-growing season. Applying water more carefully in smaller amounts does require more management effort, and this may discourage some farmers from taking up the alternative methods. On the other hand, as the value and cost of water and nutrients increases, earlier calculations will change over time. Further, the reward of higher yield and greater factor productivities in general with SRI will make the alternative methods increasingly attractive, particularly for the small, resource-constrained farmers.

Conclusion

Our results showed that under SRI management compared to TF, more nutrients (N, P, and K) are taken up by rice plants during their growth with more nutrient translocation to the grains. Further, SRI with reduced irrigation water requirements significantly increased the internal use efficiency of nutrients (N, P, and K) and the plants' water use efficiency. Due to the increasing fertilizer costs that farmers face, along with the irrigation water shortages that are increasingly occurring, and given the growing pollution/environmental problems that are foreseeable in future decades, it makes sense to conduct more research on SRI practices, with different rice varieties and different rice-growing seasons.

Moreover, appropriate water management should be studied systematically, to know what schedule of water applications and what amounts of water will give best results under what soil and climatic conditions, together with other SRI practices. Such studies should, examine also the relationships among root systems, nutrient uptake, and yield.

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References

Bhuiyan SL (1992) Water management in relation to crop production: case study on rice. Outlook Agric 21:293–299

Bonkowski M (2004) Protozoa and plant growth: the microbial loop in soil revisited. New Phytol 162:616–631

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

Chen HZ, Zhu DF, Rao LB, Lin XQ, Zhang YP (2006) Effects of SRI technique on population quality after heading stage and yield formation in rice, in Chinese with English summary. J Huazhong Agric Univ 25:483–487 in Chinese

FAO (2001) FAO statistical databases. Food and agriculture organization of the United Nations, Rome

Guerra LC, Bhuiyan SI, Tuong TP, Barker R (1998) Producing more rice with less water from irrigated systems. SWIM paper 5. IWMI/IRRI, Colombo

Iswandi I, Rupela OP, Thiyagarajan TM, Uphoff N (2011) A review of studies on SRI effects on beneficial organisms in rice soil rhizospheres. Paddy Water Environ (forthcoming)

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

Kronzucker HJ, Siddiqui MY, Glass ADM, Kirk GJD (1999) Nitrate-ammonium synergism in rice: a subcellular flux analysis. Plant Physiol 119:1041–1045

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

Li GH, Xue LH, Gu W, Yang CD, Wang SH, Ling QH, Qin X, Ding HF (2009) Comparison of yield components and plant type characteristics of high-yield rice between Taoyuan, a 'special eco-site' and Nanjing, China. Field Crops Res 112: 214–221

Liang YM, Lin XQ, Sun YF, Zhu DF, Shi GA (2004) Study on yield and its components of Xieyou 9308 under the system of rice intensification. Chin Agric Sci Bull 20:84–86 in Chinese

Lin XQ, Zhou WJ, Zhu DF (2005) The photosynthetic rate and water use efficiency of leaves at different position at panicle initiation stage under the System of Rice Intensification (SRI). Chin J Rice Sci 19:200–206 in Chinese

Lin XQ, Zhou WJ, Zhu DF, Chen HZ, Zhang YP (2006) Nitrogen accumulation remobilization and partitioning in rice (*Oryza sativa* L.) under an improved irrigation practice. Field Crops Res 96:448–454

Long X, Ma J, Xu FY, Wang HZ, Huang QL, Yuan ZX (2005) Study on the seedling-age and planting density in SRI. J Sichuan Agric Univ 23:365–373 in Chinese

Maclean JL, Dawe DC, Hardy B, Hettel GP (2002) Rice Almanac, 3rd edn. International Rice Research Institute, Los Baños

Mishra A, Salokhe VM (2008) Seedling charactistics and the early growth of transplanted rice under different water regimes. Exp Agric 44:1–19

Nguyen NV, Ferrero A (2006) Meeting the challenges of global rice production. Paddy Water Environ 4:1–9

Olaleye AO, Tabi FO, Ogunkunle AO, Sahrawat KL (2001) Effect of toxic iron concentrations on the growth of lowland rice. J Plant Nutr 24:441–457

Peng SB, Buresh RJ, Huang JL, Yang JC, Zou YB, Zhong XH, Wang GH, Zhang FS (2006) Strategies for overcoming low agronomic nitrogen use efficiency in irrigated rice systems in China. Field Crops Res 96:37–47

Prasertsak A, Fukai S (1997) Nitrogen availability and water stress interaction on rice growth. Field Crops Res 52:249–260

Rupela OP, Wani SP, Kranthi M, Humayun P, Satyanarayana A, Goud V, Gujja B, Punnarao P, Shashibhushan V, Raju DJ, Reddy PL (2006) Comparing soil properties of farmers' fields growing rice by SRI and conventional methods. In: 1st National SRI Symposium, Worldwide Fund for Nature-ICRISAT, Patancheru, Hyderabad, 17–18 November 2006

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

Satyanarayana A (2005) System of rice intensification—an innovative method to produce more with less water and inputs. In: 4th IWMI-Tata Annual Partner's Meeting. Institute for Rural Management, Anand

Si T (2000) Suggestion and discussion of several problems on water saving rice production in China, in Chinese. Irrig Drain 19:30–33

Stoop WA, Uphoff N, Kassam A (2002) A review of agricultural research issues raised by the system of rice intensification (SRI) from Madagascar: opportunities for improving farm systems for resource-poor farmers. Agric Syst 71:249–274

Tang QY, Feng MG (2002) Practical application of statistics analysis and data processing system. Science Press, Beijing

Tao SS, Ma J (2003) Improvement of the system of rice intensification (SRI) and its application in medium hybrid rice of the double cropping system. Hybrid Rice 18:47–48 in Chinese

Tuong TP, Bouman BAM (2003) Rice production in water-scarce environments. In: Kijne JW, Barker R, Molden D (eds) Water productivity in agriculture: limits, opportunities for improvement. CABI Publishing, Wallingford, pp 53–67

Uphoff N, Fernandes ECM, Yuan LP, Peng JM, Rafaralahy S, Rabenandrasana J (eds) (2002) Assessment of the system of rice intensification (SRI). In: proceedings of the international conference, Sanya, China, 1–4 April 2002. Cornell international institute for food, agriculture and development, Ithaca (http://ciifad.cornell.edu./sri/proccontents.html)

Wang SH, Cao WX, Jiang D, Tai DB, Zhu Y (2003) Effects of SRI technique on physiological characteristics and population development in rice. Chin J Rice Sci 17:31–36 in Chinese

Xu FY, Ma J, Wang HZ, Liu HY, Huang QL, Ma WB, Ming DF (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

Yang CM, Yang LZ, Yang YX, Ouyang Z (2004) Rice root growth and nutrient uptake as influenced by organic manure in continuously and alternately flooded paddy soils. Agric Water Manag 70:67–81

Yang C, Yang L, Ouyang Z (2005) Organic carbon and fraction in paddy soil as affected by different nutrient and water regimes. Geoderma 124:133–142

Yu HM, Zhu FQ, Wang CL (2003) A preliminary report of the application of the high-yielding techniques of SRI in single cropping hybrid rice. Hybrid Rice 19:33–35 in Chinese

Yu AY, Wu ZQ, Lin XQ, Zhu GP, Zhou NT, Chen DL, Shen YM (2005) Optimization of high-yield cultural practice under the system of rice intensification. Chin Agric Sci Bull 21:162–164 in Chinese

Yuan LP (2001) The system of rice intensification. Hybrid Rice 16:1–3 in Chinese

Zhao LM, Wu LH, Li YS, Lu XH, Zhu DF, Uphoff N (2009) 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 LM, Wu LH, Li YS, Sarkar A, Zhu DF, 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

Zhong HM, Huang AM, Liu JP, Li JN, Wu FB, Ouyang FP (2003) Analysis on the yield-increasing effects and economic benefits of the system of rice intensification (SRI) in hybrid rice. Hybrid Rice 18:45–46 in Chinese

Zhu DF et al (2006) The theory and practice of SRI. Agricultural Science and Technology Press, Beijing In Chinese