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Improving nitrogen fertilization in rice by site-specific N management. A review — Source link

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Review article

Improving nitrogen fertilization in rice by site-specific N management. A review*

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Abstract – Excessive nitrogen (N) application to rice (*Oryza sativa* L.) crop in China causes environmental pollution, increases the cost of rice farming, reduces grain yield and contributes to global warming. Scientists from the International Rice Research Institute have collaborated with partners in China to improve rice N fertilization through site-specific N management (SSNM) in China since 1997. Field experiments and demonstration trials were conducted initially in Zhejiang province and gradually expanded to Guangdong, Hunan, Jiangsu, Hubei and Heilongjiang provinces. On average, SSNM reduced N fertilizer by 32% and increased grain yield by 5% compared with farmers' N practices. The yield increase was associated with the reduction in insect and disease damage and improved lodging resistance of rice crop under the optimal N inputs. The main reason for poor fertilizer N use efficiency of rice crop in China is that most rice farmers apply too much N fertilizer, especially at the early vegetative stage. We observed about 50% higher indigenous N supply capacity in irrigated rice fields in China than in other major rice-growing countries. Furthermore, yield response of rice crop to N fertilizer application is low in China, around 1.5 t ha^{-1} on average. However, these factors were not considered by rice researchers and extension technicians in determining the N fertilizer rate for recommendation to rice farmers in China. After a decade of research on SSNM in China and other Asian rice-growing countries, we believe SSNM is a matured technology for improving both fertilizer N use efficiency and grain yield of rice crop. Our challenges are to further simplify the procedure of SSNM and to convince policy-makers of the effectiveness of this technology in order to facilitate a wider adoption of SSNM among rice farmers in China.

site-specific nitrogen management / nitrogen use efficiency / grain yield / nitrogen response / rice / China

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1. INTRODUCTION

Increase in fertilizer nutrient input, especially N fertilizer, has contributed significantly to the improvement of crop yields in the world (Cassman et al., 2003). Development of semi-dwarf rice (*Oryza sativa* L.) varieties in the 1960s assured the achievement of high grain yield under increased N fertilizer rates because of their lodging resistance at high N inputs (Yoshida, 1972). To maximize grain yield, farmers often apply a higher amount of N fertilizer than the minimum required for maximum crop growth (Lemaire and Gastal, 1997). Over-application of N fertilizer may actually decrease grain yield by increasing susceptibility to lodging (Pham et al., 2004) and damage from pests and diseases (Cu et al., 1996).

China is currently the world's largest consumer of N fertilizer. In 2006, annual N fertilizer consumption in China was 31 million metric tons or 31.7% of the global N consumption (Heffer, 2008). About 18% of this N was used for rice production in China (Heffer, 2008). China accounts for about 19% of the world's rice planting area and produced 29% of global rice production in 2006 (FAOSTAT, 2008). Rice crops in China use about 36% of the total N fertilizer used for rice production in the world (Heffer, 2008).

There are several sources of information on the average N rate of rice production in China. The International Fertilizer Industry Association (IFA, 2002) reported that China's national average N rate for rice was 145 kg ha^{-1} in 1997. Based on data from 1995 to 1997, the average rate of N application for rice production in China was 180 kg ha^{-1} (FAO, unpublished data, 2001). If we use the data for the rice planting area from FAOSTAT and N consumption for rice from Heffer (2008), China's national average N rate for rice was 193 kg ha^{-1} in 2006, about 90% higher than the world average (FAOSTAT, 2008; Heffer, 2008). Nitrogen rates of 150 to 250 kg ha^{-1} are common (Wang et al., 2001; Peng et al., 2006). In Jiangsu Province, China, the average N rate reached 300 kg ha^{-1} in some counties (Q. Zhu, pers. commun., 2001). Average rice grain yield in China was 6.27 t ha^{-1} in 2006, about 53% higher than the world average (FAOSTAT, 2008). Rice crop in China received twice as much N fertilizer as in Japan but the grain yield was similar in the two countries.

Fertilizer N use efficiency can be measured in different ways using N-omission plots (Novoa and Loomis, 1981). The yield increase that results from N application in comparison with no N application is defined as the agronomic N use efficiency (kg grain yield increase per kg N applied). The apparent recovery efficiency of fertilizer N is used to express the percentage of fertilizer N recovered in aboveground plant biomass at the end of the cropping season. Yield response of rice crop to N fertilizer application is defined as N response, which is calculated as the difference between yields with and without N fertilizer (IRRI, 2006). The partial factor productivity from applied N is the ratio of grain yield to N applied and it provides an integrative index that quantifies total economic output relative to utilization of all N resources in the system, including indigenous soil N and fertilizer N (Cassman et al., 1996b). This parameter for quantifying fertilizer N use efficiency does not need N-omission plots.

The high rates of N fertilizer input and improper timing of N application in China have led to low recovery efficiency and agronomic N use efficiency. Zhu (1985) reported that recovery efficiency in China was less than 30% for ammonium bicarbonate and 30–40% for urea. Li (1997) estimated that recovery efficiency for rice in China was around 30–35%. However, Li (2000) observed that the average recovery efficiency of rice in Jiangsu Province was only 20%. This was further confirmed by Wang et al. (2001), who reported that recovery efficiency of farmers' N fertilizer practice was 18% in an on-farm experiment conducted in Zhejiang. Peng et al. (2006) found that recovery efficiency of farmers' N fertilizer practice was 20 to 30% in four provinces in China.

Yoshida (1981) estimated agronomic N use efficiency to be 15–25 kg rough rice per kg applied N in the tropics. Cassman et al. (1996b) reported that agronomic N use efficiency was 15 to 18 kg kg^{-1} N in the dry season in the farmers' fields in the Philippines. In China, agronomic N use efficiency was 15–20 kg kg^{-1} N from 1958 to 1963 and declined to only 9.1 kg kg^{-1} N between 1981 and 1983 (Lin, 1991). Since then, agronomic N use efficiency has further decreased in China because of the increase in N rate (Peng et al., 2002). Wang et al. (2001) reported that agronomic N use efficiency of farmers' N fertilizer practice was 6.4 kg kg^{-1} in Zhejiang. Peng et al. (2006) reported that rice yield increases by only 5 to 10 kg for every kg of N fertilizer input by using farmers' N fertilizer practice in China.

2. SSNM PRINCIPLES AND PROCEDURES

Site-specific N management (SSNM) was developed to increase fertilizer N use efficiency of irrigated rice (Dobermann et al., 2002). In SSNM, N application is based on the crop demand for N. Climatic factors (solar radiation and temperature) and indigenous N supply largely affect crop N demand. Indigenous N supply includes N from soil mineralization, irrigation water and crop residues. Soil chemical analysis is not reliable to quantify indigenous N supply for paddy soil (Cassman et al., 1996a). Therefore, the measurement of grain yield in N-omission plots is used to obtain field-specific estimates of the indigenous N supply (Cassman et al., 1996b). During the growing season, leaf N status measured with a chlorophyll meter (SPAD) or leaf color chart is a good indicator of crop N demand (Peng et al., 1996). Both the SPAD and leaf color chart provide a good estimation of leaf N content on a leaf-area basis (Peng et al., 1993; Yang et al., 2003). In-season upward or downward adjustments of predetermined N topdressings at critical growth stages are made based on SPAD or leaf color chart readings at these stages. In this approach, the timing and number of N applications are fixed while the rate of N topdressing varies across seasons and locations.

In current SSNM practice, four steps are needed to estimate total N rate based on indigenous N supply capacity and target yield: (1) set an attainable yield target based on 85% of yield potential, (2) estimate indigenous N supply – yield without N fertilizer, (3) estimate N response – the difference between target yield and yield without N fertilizer, and (4) estimate N rate based on N response and agronomic N use efficiency. A realistic target agronomic N use efficiency is chosen by considering the yield and agronomic N use efficiency of the location in previous seasons (IRRI, 2006). The total N is distributed at one day before transplanting, midtillering, panicle initiation and heading with approximate proportions of 35, 20, 30 and 15%, respectively (Peng et al., 2006). The pre-determined N rate is 30 kg ha^{-1} at midtillering and 40 kg ha^{-1} at panicle initiation. The actual rates of N topdressing at midtillering and panicle initiation are adjusted by ±10 kg N ha^{-1} according to leaf N status measured with a SPAD or leaf color chart. When leaf N is below the low level of the SPAD or leaf color chart thresholds, N rate will be increased by 10 kg ha^{-1}; when leaf N is greater than the upper level of the SPAD or leaf color chart thresholds, it will be decreased by 10 kg ha^{-1}. No adjustment in N rate is needed when leaf N is within the thresholds. At heading, N is applied only if leaf N is below the SPAD or leaf color chart thresholds. We used the same SPAD and leaf color chart thresholds across different growth stages for a given variety (Peng et al., 1996). The SPAD and leaf color chart thresholds vary with varieties, which needs to be determined experimentally. Japonica generally requires higher thresholds than indica. For example, SPAD thresholds of 35–37 were used for indica varieties and they were 2 units higher for japonica varieties (Huang et al., 2008). The SPAD value of 35 corresponded to a leaf color chart score of 3.2, 4.8 and 5.2 for the leaf color charts developed by the International Rice Research Institute (IRRI), Zhejiang Agricultural University, China, and University of California-Davis, USA, respectively (Yang et al., 2003).

The procedures of SSNM can be simplified in two ways. Firstly, if there is no N-omission plot and its grain yield is unknown, one can estimate the N response based on the information of climatic yield potential and soil fertility (i.e. skipping the first two steps in estimating total N rate). Secondly, if farmers do not want to measure leaf N status using the SPAD or leaf color chart, upward or downward adjustments of N topdressings can be made based on visual leaf N status (IRRI, 2006).

Since 1997, SSNM has been evaluated in farmers' fields in eight major irrigated rice domains in Asia (Dobermann et al., 2002), including rice farms in Zhejiang Province, China (Wang et al., 2001, 2004). Across all sites in Asia, average grain yield increased by 11% and average recovery efficiency increased from 31% to 40%, with 20% of all farmers achieving more than 50% recovery efficiency (Dobermann et al., 2002).

3. IRRI-CHINA COLLABORATION ON SSNM RESEARCH

IRRI scientists in collaboration with partners in China have started research work on improving rice N fertilization through SSNM in China since 1997 (Wang et al., 2001). Field experiments were conducted initially in Zhejiang province in 1997 and gradually expanded to Guangdong, Hunan and Jiangsu provinces in 2001, to Hubei province in 2003, and to Heilongjiang province in 2005 (Peng et al., 2006). These six provinces occupy about 45% of the rice planting area in China. Collaborating organizations in China are Zhejiang University, Guangdong Academy of Agricultural Sciences, Hunan Agricultural University, Yangzhou University, Huazhong Agricultural University, Northeast Agricultural University, China Agricultural University and the Chinese Academy of Sciences.

From 1997 to 2000, on-farm demonstration of SSNM was conducted in Zhejiang province in farmers' fields by comparing SSNM with farmers' N fertilizer practice (Wang et al., 2001, 2004). From 2001 to 2003, SSNM was compared with other N treatments including real-time N management, farmers' N fertilizer practice, modified farmers' N fertilizer practice, and three fixed-N split treatments in the replicated on-farm trials in Zhejiang, Guangdong, Hunan and Jiangsu provinces (Peng et al., 2006). In real-time N management, N was applied only when the leaf N content was below a critical level. The farmers' N fertilizer practice was modified by reducing the total N rate by 30% and this reduction was restricted to within 10 days after transplanting. The three fixed-N split treatments had total N rates of 60, 120 and 180 kg ha^{-1} with 35% applied at basal, 20% at midtillering, 30% at panicle initiation, and 15% at heading. From 2005 to 2007, SSNM was compared with the real-time N management using four SPAD thresholds in the replicated on-farm trials in Guangdong, Hunan, Hubei and Jiangsu provinces. Overall, SSNM performed better than the real-time N management and the modified farmers' N fertilizer practice because the total N rate of SSNM was closer to the optimal level. In on-farm demonstration and farmer participatory research, we focused mainly on SSNM technology for improving fertilizer N use efficiency in irrigated rice in China.

On-farm demonstration of SSNM was done in the six provinces from 2003 to 2007. Only one location was chosen in each province. About 10 farmers from each location participated in the demonstration experiment. Each farmer's field had three treatments: farmers' N fertilizer practice, SSNM and N omission. The field was divided into two equal parts with a levee, and farmers' N fertilizer practice and SSNM treatments were randomly assigned to each half of the field. The N-omission plot (5 m × 5 m) was installed in the half of the field with SSNM treatment. In the farmers' N fertilizer practice, farmers apply N fertilizer (form, rate and timing) based on their own decision. Other crop management practices including P and K application were identical among the three treatments.

We used farmer participatory research for on-farm testing of N fertilization by standard and farmer-modified SSNM for irrigated rice in Guangdong, Hunan, Hubei and Jiangsu provinces from 2003 to 2005 (Hu et al., 2007). Twelve to 15 farmers were randomly selected in each study village in each year for a dialogue with the research team and for a rapid rural technology assessment. Based on the information obtained from the rapid rural technology assessment, modified SSNM schemes were developed through dialogue between a research team and farmers at a workshop in each village. Modification mainly involved decreasing the number of N fertilizer topdressings and increasing the rate of basal N application. Based on the farmers' willingness, 144 farmers

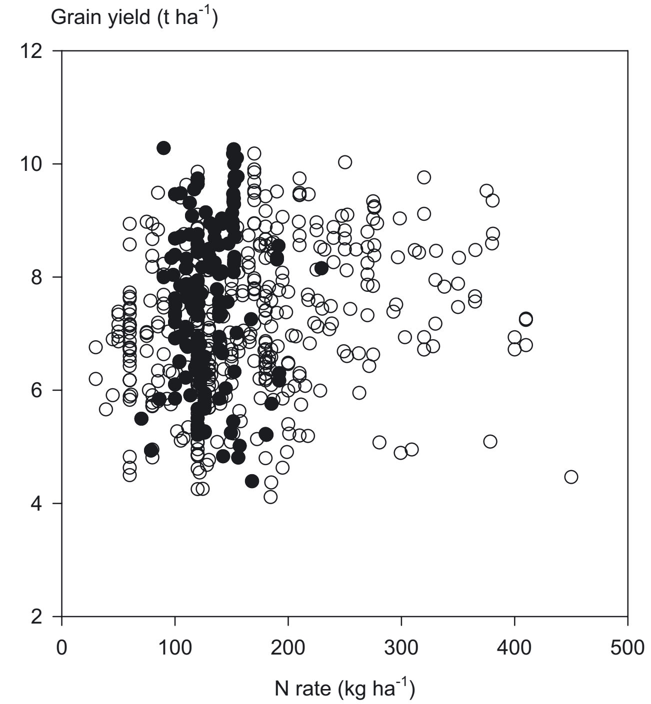

Figure 1. Grain yield and N rate of site-specific N management (solid symbols) and other N treatments (open symbols). Data are from on-farm field trials, on-farm demonstration and farmer participatory research conducted in six provinces in China from 2001 to 2007.

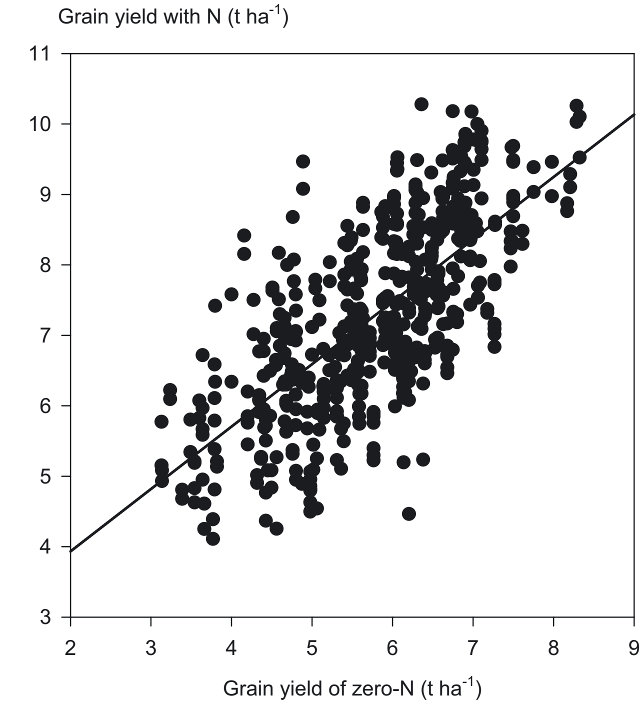

Figure 2. Relationship between grain yield with and without N fertilizer. Data are from on-farm field trials, on-farm demonstration and farmer participatory research conducted in six provinces in China from 2001 to 2007. y = 2.16 + 0.886x (r = 0.70; n = 544).

were selected to conduct an experiment to compare SSNM or modified SSNM with farmers' N fertilizer practice.

Data from on-farm field trials, on-farm demonstration and farmer participatory research in the six provinces in China from 2001 to 2007 were pooled to compare SSNM with farmers' N fertilizer practice and other N treatments. The same dataset was used to determine the relationships among yield with N fertilizer, zero-N yield, N response and agronomic N use efficiency. There were 544 observations for these analyses. Data from the on-farm demonstration of SSNM in Zhejiang province from 1997 to 2000 were published elsewhere (Wang et al., 2001, 2004) and not included in the analyses of this paper.

4. KEY RESEARCH FINDINGS

There were wide ranges in both grain yield and total N rate across all experiments (Fig. 1). Grain yield varied from 4 to 10 t ha^{-1} with an average of 7.28 t ha^{-1}, while total N rate ranged from 50 to 400 kg ha^{-1} with a mean of 157 kg ha^{-1}. SSNM was able to narrow the range of total N rate to 80–200 kg ha^{-1} with a mean of 120 kg ha^{-1}. There was no correlation between grain yield and total N rate. This poor relationship was caused by many factors including location, season, variety, pest damage, other crop management practices, etc., which affected grain yield aside from total N rate.

We observed a relatively high indigenous N supply capacity in irrigated rice fields in China compared with other major rice-growing countries. Crop N uptake at maturity when N fertilizer was not applied was in the range of 90–100 kg ha^{-1}, compared with 60–70 kg ha^{-1} under tropical conditions (Dobermann et al., 2003). Grain yield of zero-N control ranged from 3 to 8 t ha^{-1} and averaged at 5.77 t ha^{-1} (Fig. 2). There was a positive relationship between grain yields with and without N fertilizer.

Averaged across 107 farmers who conducted on-farm demonstration, SSNM produced 5% higher grain yield than farmers' N fertilizer practice (Tab. I). The yield increase was associated with the reduction in insect and disease damage and improved lodging resistance of rice crop under the optimal N inputs (Zhong et al., 2006a, b). This small yield increase was achieved when total N rate was reduced from 195 to 133 kg ha^{-1}, a 32% saving of N fertilizer over farmers' N fertilizer practice. The N response of SSNM was 28% higher than that of farmers' N fertilizer practice. Consequently, SSNM almost doubled farmers' N fertilizer practice in agronomic N use efficiency, and had 55% higher partial factor productivity of applied N than farmers' N fertilizer practice. Similar results were obtained when SSNM was compared with other N treatments such as real-time N management, farmers' N fertilizer practice, modified farmers' N fertilizer practice, and fixed-N split treatments in 25 replicated on-farm trials in five provinces between 2001 and 2007 (Tab. II). Yield increase was insignificant but SSNM saved 25% N fertilizer over other N treatments. SSNM increased N response by 15%, agronomic N use efficiency by 55%, and partial factor productivity of applied N

Table I. Grain yield, total N rate, yield response to N application, agronomic N use efficiency, and partial factor productivity of applied N (PFP) of farmers' fertilizer practice and site-specific N management (SSNM). Data were from on-farm demonstrations conducted by 107 farmers from six provinces in China between 2003 and 2007. Average grain yield of zero-N control was 5.69 t ha^{-1} across the 107 farmers.

Parameters	Farmers' practice	SSNM	Difference (%)
Grain yield (t ha^{-1})	7.08 b	7.47 a	5
N rate (kg ha^{-1})	195 a	133 b	38
N response (t ha^{-1})	1.39 b	1.78 a	25
Agronomic N use efficiency (kg kg^{-1})	7.1 b	13.4 a	61
PFP (kg kg^{-1})	36.3 b	56.2 a	43

Within a row, means followed by different letters are significantly different at the 0.05 probability level according to the least significant difference (LSD) test.

Table II. Grain yield, total N rate, yield response to N application, agronomic N use efficiency, and partial factor productivity of applied N (PFP) of fixed N-rate treatments and site-specific N management (SSNM). Data were from 25 on-farm field experiments conducted in five provinces in China between 2001 and 2007. Average grain yield of zero-N control was 5.87 t ha^{-1} across the 25 experiments.

Parameters	Other N treatments	SSNM	Difference (%)
Grain yield (t ha^{-1})	7.45 a	7.69 a	3
N rate (kg ha^{-1})	161 a	120 b	29
N response (t ha^{-1})	1.58 a	1.82 a	14
Agronomic N use efficiency (kg kg^{-1})	9.8 b	15.2 a	43
PFP (kg kg^{-1})	46.3 b	64.1 a	32

Within a row, means followed by different letters are significantly different at the 0.05 probability level according to the least significant difference (LSD) test.

by 38% compared with other N treatments. In farmer participatory research, the rate and distribution of N fertilizer during the growing season of modified SSNM were in between those of SSNM and farmers' N fertilizer practice (Hu et al., 2007). Both SSNM and modified SSNM, compared with farmers' N fertilizer practice, maintained rice yields with significantly less N fertilizer and no significant increase in total labor input. The reduction in N fertilizer input averaged 48 kg ha^{-1} for SSNM and 23 kg ha^{-1} for modified SSNM.

Large variation in N response was observed across 544 observations (Fig. 3). The 1.5 t ha^{-1} average N response across all experiments is very low compared with the average N response of 3.0 t ha^{-1} observed under tropical conditions (Dobermann et al., 2003). Negative N response occurred when the application of N fertilizer actually reduced grain yield. Yield reduction was often observed under excessive N input due to greater pest damage and lodging. There was no correlation between N response and total N rate. High total N rates did not result in high N response. The N response was correlated positively with grain yield when N was applied (Fig. 4). There was a negative but weak correlation between N response and the grain yield of zero-N control.

There was a negative relationship between agronomic N use efficiency and total N rate (Fig. 5). Large variation in agronomic N use efficiency was observed when total N rates were between 80 and 120 kg ha^{-1}. When total N rates were greater than 300 kg ha^{-1}, agronomic N use efficiency was below 10 kg kg^{-1}. Negative agronomic N use efficiency was observed when grain yield was reduced by the application of N fertilizer. Like N response, agronomic N use efficiency was correlated positively with the grain yield of N-applied treatments but negatively with the grain yield of zero-N control (Fig. 6).

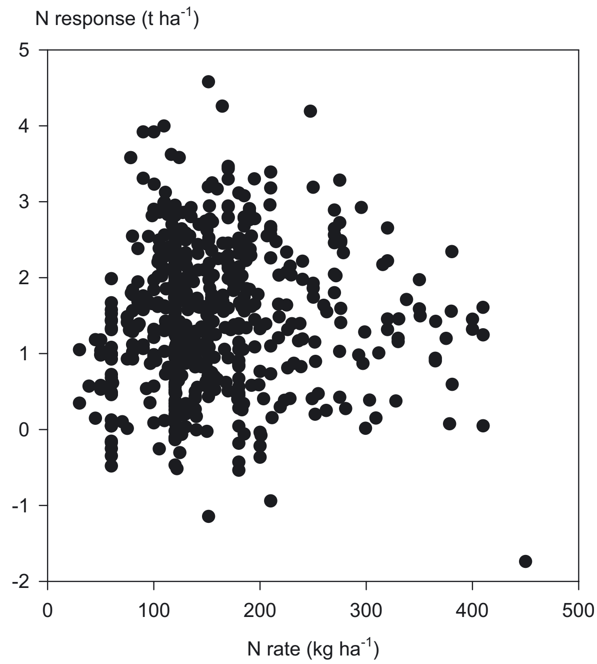

Figure 3. Relationship between yield response to N application (N response) and N rate. Data are from on-farm field trials, on-farm demonstration and farmer participatory research conducted in six provinces in China from 2001 to 2007.

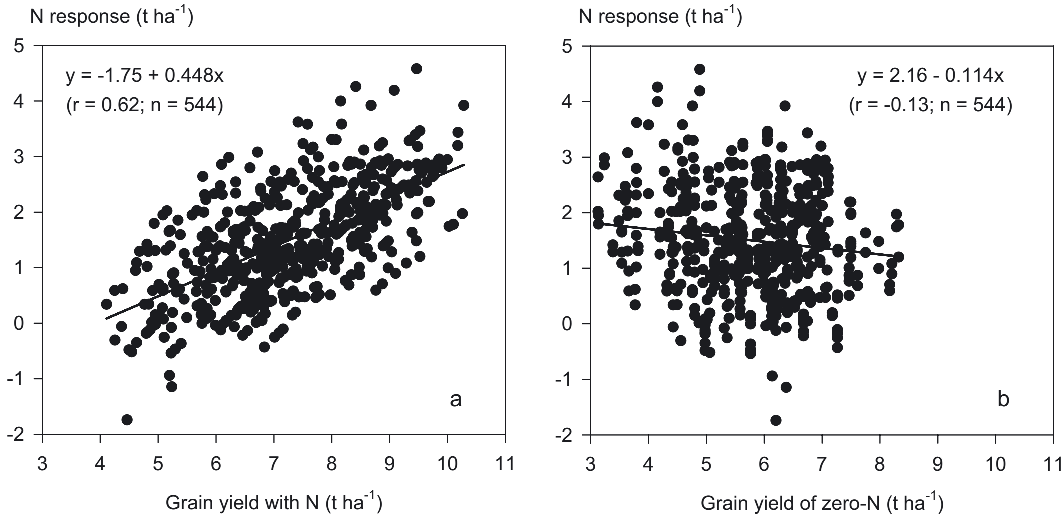

Figure 4. Relationship between yield response to N application (N response) and grain yield with N fertilizer (a) and grain yield without N fertilizer (b). Data are from on-farm field trials, on-farm demonstration and farmer participatory research conducted in six provinces in China from 2001 to 2007.

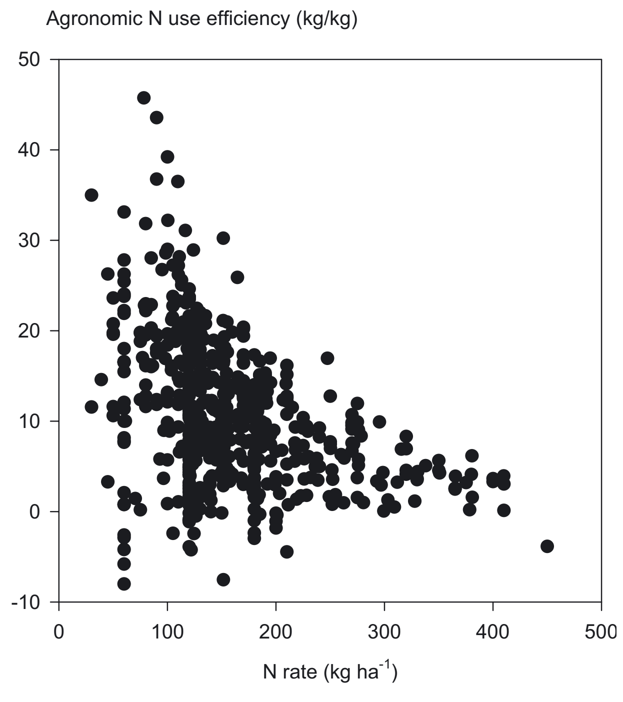

Figure 5. Relationship between agronomic N use efficiency and N rate. Data are from on-farm field trials, on-farm demonstration and farmer participatory research conducted in six provinces in China from 2001 to 2007.

Grain yield and total N rate were generally higher in the North than in the South. Grain yield of zero-N control suggests that indigenous N supply was the lowest in Guangdong compared with the other five provinces. The N response and agronomic N use efficiency were the highest in Heilongjiang compared with the other five provinces. Therefore, there is a great potential to improve N management through SSNM in the provinces where total N rate is high and agronomic N use efficiency is low.

The main reason for poor fertilizer N use efficiency of rice crop in China is that most rice farmers apply excess N fertilizer, especially at the early vegetative stage (Peng et al., 2006). High indigenous N supply capacity and low N response were not considered by rice researchers and extension technicians when N fertilizer rate was determined for recommendation to rice farmers in China. This explains why SSNM usually have a lower total N rate than farmers' N fertilizer practice in China. A twelve-season long-term field experiment demonstrated that a decrease in total N rate may reduce indigenous N supply capacity, but will not cause yield reduction in subsequent rice crops as long as optimal N management is practiced (data not shown).

5. REMARKS ON SITE-SPECIFIC N MANAGEMENT

Improved N management such as SSNM increases both grain yield and fertilizer N use efficiency compared with farmers' N fertilizer practice in China. This is achieved by reducing total N rate and by reducing N rate during the early vegetative stage. The total N rate is reduced because of small N response and high target agronomic N use efficiency. The reduction in N rate during the early vegetative stage is considered because irrigated rice soils in China have a high indigenous N supply capacity, which provides sufficient N for the early vegetative growth. In implementing the SSNM procedure, we have two steps to determine the right N rate for rice crop. The first step is done before crop establishment. The total N rate is estimated based on N response and target agronomic N use efficiency. The percentage of the first N application is decided based on previous experimental results and indigenous N supply capacity. The second step is the upward or downward adjustments

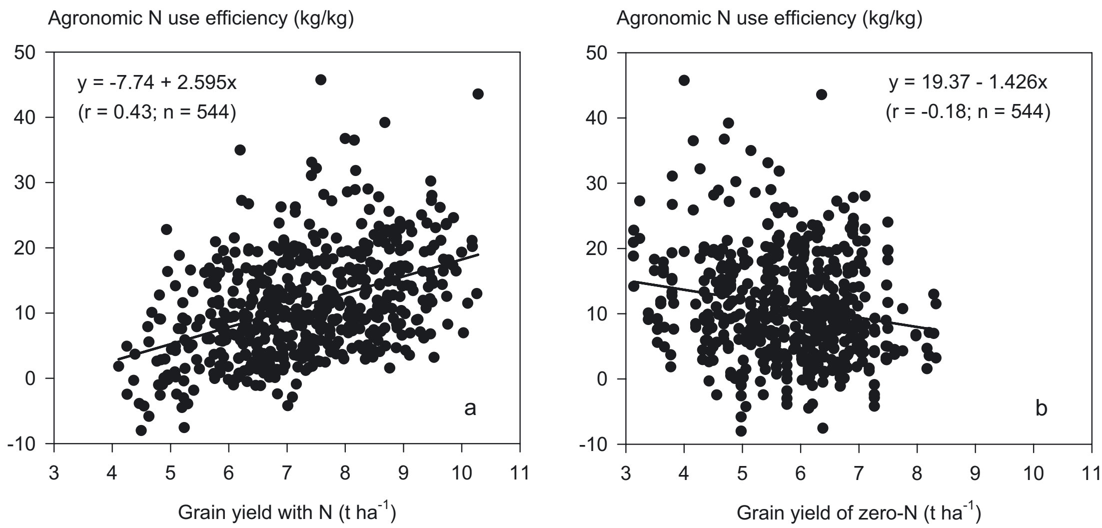

Figure 6. Relationship between agronomic N use efficiency and grain yield with N fertilizer (a) and grain yield without N fertilizer (b). Data are from on-farm field trials, on-farm demonstration and farmer participatory research conducted in six provinces in China from 2001 to 2007.

of topdressing N rate by 10 kg N ha^{-1} at critical growth stages based on leaf N status.

Several limitations are associated with SSNM. First of all, grain yield of zero-N control varies with cropping history, variety, climatic conditions and crop management practices. As a consequence, N response is not very stable for a given location across seasons. Secondly, agronomic N use efficiency is affected by many factors such as N response and total N rate. Therefore, total N rate determined by N response and agronomic N use efficiency provides only an approximate range. Thirdly, varietal differences in tillering capacity and early growth vigor are not considered when the percentage of the first N application is decided. Finally, the in-season adjustment of N rate by ±10 kg ha^{-1} may be inadequate because more adjustment could be needed when yield level and the magnitude of N response are high. Because of these limitations, only 3–5% increase in grain yield can be achieved by SSNM in China. Furthermore, SSNM improved agronomic N use efficiency only up to an average of 15 kg kg^{-1} in China. Future research should focus on accurate determination of N response and agronomic N use efficiency using weather data such as solar radiation and air temperature, and information on variety and soil characteristics. Experiments are needed to test if in-season adjustment of N rate should be linked with the difference between actual SPAD readings and SPAD threshold values.

Several problems exist in the adoption of SSNM technology. First of all, information on the yield of N-omission plots and target yield are not available to many farmers. Secondly, N response is variable and largely affected by variety, crop management practices, season and location. Thirdly, some farmers are reluctant to invest time in monitoring leaf N status using the leaf color chart. Many farmers have difficulty in determining leaf color chart readings accurately. Fourthly, frequent changes in varieties require adjustments in leaf color chart threshold values. Finally, the procedures for implementing SSNM could be complicated for many farmers. These problems may be overcome by developing remote sensing technology such as a canopy reflectance sensor or satellite remote sensing for determining the timing and rate of fertilizer N topdressing during the rice-growing period (Xue and Yang, 2008).

Despite the above limitations, a decade of collaborative research work on SSNM between IRRI and Chinese scientists has changed the perception of researchers and farmers about N fertilizer management in irrigated rice in China. The following concepts are accepted now by many rice researchers in China: (1) target yield and indigenous N supply capacity should be considered when total N rate is determined; (2) determination of N application rate at basal and during the early vegetative stage should also be based on indigenous N supply; (3) the rate of N topdressing depends on leaf N status and crop N demand, and (4) regional blanket recommendation for N management will not work well. Nowadays, many researchers have developed local N management practices based on SSNM principles and by integration with other management practices. Many farmers who have been exposed to SSNM understand that it is not true that "the higher the N fertilizer input, the higher the grain yield" and that "the greener the leaves, the better the rice crop". They know that it is necessary to reduce N input at basal and the early vegetative stage and increase N input at late stages. The dynamic change in leaf N status has been embedded in some farmers' minds. They can judge visually when and how much N should be applied without using the leaf color chart.

6. CONCLUSIONS

After one decade of research on SSNM in China and other Asian rice-growing countries, we believe SSNM is a matured technology for improving both fertilizer N use efficiency and grain yield of irrigated rice crop. Our study suggests that there is potential for large-scale dissemination of SSNM technology in China. Accurate estimation of N response and selection of the right agronomic N use efficiency are needed for a better performance of SSNM. In-season adjustment in N rate should also consider the differences in location, season and variety. SSNM principles are useful for researchers to develop N management practices for their local conditions. Our challenges are to further simplify the procedure of SSNM and to convince policy-makers of the effectiveness of this technology in order to facilitate a wider adoption of SSNM among rice farmers in China. Future research is needed to develop SSNM based on remote sensing technology so that SSNM can be practiced on a large scale.

REFERENCES

Cassman K.G., Dobermann A., Sta Cruz P.C., Gines G.C., Samson M.I., Descalsota J.P., Alcantara J.M., Dizon M.A., Olk D.C. (1996a) Soil organic matter and the indigenous nitrogen supply of intensive irrigated rice systems in the tropics, Plant Soil 182, 267–278.

Cassman K.G., Dobermann A., Walters D.T., Yang H.S. (2003) Meeting cereal demand while protecting natural resources and improving environmental quality, Ann. Rev. Environ. Resour. 28, 315–358.

Cassman K.G., Gines G.C., Dizon M.A., Samson M.I., Alcantara J.M. (1996b) Nitrogen-use efficiency in tropical lowland rice systems: contributions from indigenous and applied nitrogen, Field Crops Res. 47, 1–12.

Cu R.M., Mew T.W., Cassman K.G., Teng P.S. (1996) Effect of sheath blight on yield in tropical, intensive rice production system, Plant Disease 80, 1103–1108.

Dobermann A., Witt C., Abdulrachman S., Gines H.C., Nagarajan R., Son T.T., Tan P.S., Wang G.H., Chien N.V., Thoa V.T.K., Phung C.V., Stalin P., Muthukrishnan P., Ravi V., Babu M., Simbahan G.C., Adviento M.A.A. (2003) Soil fertility and indigenous nutrient supply in irrigated rice domains of Asia, Agron. J. 95, 913–923.

Dobermann A., Witt C., Dawe D., Gines H.C., Nagarajan R., Satawathananont S., Son T.T., Tan P.S., Wang G.H., Chien N.V., Thoa V.T.K., Phung C.V., Stalin P., Muthukrishnan P., Ravi V., Babu M., Chatuporn S., Kongchum M., Sun Q., Fu R., Simbahan G.C., Adviento M.A.A. (2002) Site-specific nutrient management for intensive rice cropping systems in Asia, Field Crops Res. 74, 37–66.

FAOSTAT (2008) FAO Statistical databases, http://www.fao.org, Food and Agriculture Organization (FAO) of the United Nations, Rome.

Heffer P. (2008) Assessment of fertilizer use by crop at the global level, International Fertilizer Industry Association (IFA), Paris, France, pp. 1–5.

Hu R., Cao J., Huang J., Peng S., Huang J., Zhong X., Zou Y., Yang J., Buresh R.J. (2007) Farmer participatory testing of standard and modified site-specific nitrogen management for irrigated rice in China, Agric. Syst. 94, 331–340.

Huang J., He F., Cui K., Buresh R.J., Xu B., Gong W., Peng S. (2008) Determination of optimal nitrogen rate for rice varieties using a chlorophyll meter, Field Crops Res. 105, 70–80.

IFA (2002) Fertilizer use by crop, 5th ed. http://www.fertilizer.org/ifa/statistics.asp, International Fertilizer Industry Association (IFA), International Fertilizer Development Center (IFDC), International Potash Institute (IPI), Potash and Phosphate Institute (PPI), and Food and Agriculture Organization (FAO).

International Rice Research Institute (IRRI) (2006) Site-specific nutrient management, www.irrri.org/irrc/ssnm/, accessed 20 March 2006.

Lemaire G., Gastal F. (1997) Nitrogen uptake and distribution in plant canopies, in: Lemaire G. (Ed.), Diagnosis of the Nitrogen Status in Crops, Springer-Verlag, Berlin, pp. 3–43.

Li Q. (1997) Fertilizer issues in the sustainable development of China agriculture, Jiangxi Science and Technology Press, China.

Li R. (2000) Efficiency and regulation of fertilizer nitrogen in high-yield farmland: A case study on rice and wheat double maturing system agriculture area of Tai lake for deducing to Jiangsu Province, Ph.D. Dissertation, China Agricultural University, Beijing, China.

Lin B. (1991) Make the most efficient use of fertilizers in increasing crop production, in: Soil Science in China: Present and Future, Soil Science Society of China, Jiangsu Science and Technology Press, China, pp. 29–36.

Novoa R., Loomis R.S. (1981) Nitrogen and plant production, Plant Soil 58, 177–204.

Peng S., Buresh R.J., Huang J., Yang J., Zou Y., Zhong X., Wang G., Zhang F. (2006) Strategies for overcoming low agronomic nitrogen use efficiency in irrigated rice systems in China, Field Crops Res. 96, 37–47.

Peng S., Garcia F.V., Laza R.C., Cassman K.G. (1993) Adjustment for specific leaf weight improves chlorophyll meter's estimate of rice leaf nitrogen concentration, Agron. J. 85, 987–990.

Peng S., Garcia F.V., Laza R.C., Sanico A.L., Visperas R.M., Cassman K.G. (1996) Increased N-use efficiency using a chlorophyll meter on high-yielding irrigated rice, Field Crops Res. 47, 243–252.

Peng S., Huang J., Zhong X., Yang J., Wang G., Zou Y., Zhang F., Zhu Q., Buresh R., Witt C. (2002) Challenge and opportunity in improving fertilizer-nitrogen use efficiency of irrigated rice in China, Agric. Sci. China 1, 776–785.

Pham Q.D., Abe A., Hirano M., Sagawa S., Kuroda E. (2004) Analysis of lodging-resistant characteristics of different rice genotypes grown under the standard and nitrogen-free basal dressing accompanied with sparse planting density practices, Plant Prod. Sci. 7, 243–251.

Wang G.H., Dobermann A., Witt C., Sun Q.Z., Fu R.X. (2001) Performance of site-specific nutrient management for irrigated rice in southeast China, Agron. J. 93, 869–878.

Wang G.H., Sun Q., Fu R., Huang X.H., Ding X.H., Wu J., He Y.F., Dobermann A., Witt C. (2004) Site-specific nutrient management in intensive irrigated rice systems of Zhejiang province, China, in: Dobermann A. et al. (Eds.), Increasing Productivity of Intensive Rice Systems through Site-specific Nutrient Management. Science Publishers, Inc., Enfield, NH (USA), and International Rice Research Institute, Los Baños, Philippines, pp. 243–263.

Xue L., Yang L. (2008) Recommendations for nitrogen fertilizer topdressing rates in rice using canopy reflectance spectra, Biosyst. Eng. 100, 524–534.

Yang W.-H., Peng S., Huang J., Sanico A.L., Buresh A.L., Witt C. (2003) Using leaf color charts to estimate leaf nitrogen status of rice, Agron. J. 95, 212–217.

Yoshida S. (1972) Physiological aspects of grain yield, Annu. Rev. Plant Physiol. 23, 437–464.

Yoshida S. (1981) Fundamentals of rice crop science. International Rice Research Institute, Los Baños, Philippines, 269 p.

Zhong X., Peng S., Buresh R.J., Huang N., Zheng H. (2006a) Some canopy indices influencing sheath blight development in hybrid rice, Chinese J. Rice Sci. 20, 535–542.

Zhong X., Zheng H., Huang N., Ou J. (2006b) Performance of site-specific nutrient management in double-season rice in South China, China Rice 3, 30–32.

Zhu Z. (1985) Research progresses on the fate of soil N supply and applied fertilizer N in China, Soil 17, 2–9.