Opportunities for yield increases and environmental benefits through site-specific nutrient management in rice systems of Zhejiang Province, China

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Abstract

Environmental pollution by nitrogen (N) leaching or runoff from rice fields and high pesticide use has become serious concern in China. Average N application rates are high and fertilizer-N use efficiency is low compared with other major rice growing countries. In Zhejiang, rice farmers apply 150-250 kg ha^{-1} fertilizer N and 7-10 sprays of pesticides per season to maintain yield levels of 5.5-8.0 t ha^{-1}. Fertilizer and pest management strategies of farmers are not based on plant nutrient demand and pest control requirements, and appear to be largely directed at risk avoidance. To provide farmers with options for high yielding, yet more resourceful management options, a new site-specific nutrient management (SSNM) approach was developed at Zhejiang University in collaboration with the International Rice Research Institute (IRRI). The main objective of this paper is to introduce SSNM as an important component of sustainable resource management in rice ecosystems. The approach comprises of guidelines that allow farmers to adjust domain- and season-specific fertilizer recommendations to actual growing conditions in their fields. Recommendations are developed for profitable grain yield targets considering plant nutrient demand, indigenous nutrient supply, nutrient balance, nutrient use efficiency, as well as socio-economic factors. The agronomic performance of SSNM has been evaluated in farmers' fields in the past seven years (1998-2004). With SSNM, average grain yield increased by about 0.5 t ha^{-1} over the farmers' practice, while N use efficiency increased significantly. About 30% of both fertilizer N and pesticides could be reduced through adoption of SSNM, which would effectively eliminate an unnecessary source

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of pollution in the rice ecosystem. Larger scale dissemination of SSNM for rice is under way in Zhejiang province, but stronger institutional support is urgently required.

Keywords: Rice; Fertilizer nitrogen; Site-specific nutrient management

1. Introduction

The concept of site-specific nutrient management (SSNM) for rice was developed in the mid-1990s and then evaluated from 1997 to 2000 in about 200 irrigated rice farms at eight sites in Asia, including one site with Zhejiang University in China (Dobermann and White, 1999; Dobermann et al., 2002). SSNM as conceptualized aimed at dynamic field-specific management of N, P, and K fertilizer to optimize the supply and demand of nutrients. The plant's need for N, P, or K fertilizer was determined from the gap between the supply of a nutrient from indigenous sources, as measured with a nutrient omission plot, and the demand of the rice crop for that nutrient, as estimated from the total nutrient required by the crop to achieve a yield target for average climatic conditions.

SSNM for N as developed and evaluated from 1997 to 2000 used a 'fixed time-adjustable dose' approach (Wang et al., 2001b; Wang et al., 2001a). A decision support system provided – before planting – a pattern for splitting an estimated total N fertilizer requirement among pre-set application times (Witt and Dobermann, 2004; Witt et al., 2005). The pre-determined N doses in the splitting pattern at critical growth stages, say, panicle initiation and flowering, were then dynamically adjusted upward or downward depending on plant growth and N requirement of growth stage, season, growth duration, and variety based on either chlorophyll meter or leaf colour chart (LCC) readings (Witt et al., 2002).

During the 1990s an alternative 'real-time' approach to N management was also developed and evaluated. With this approach, the timing of N application is not pre-set. Instead, it is dynamically adjusted to crop N demand (Peng et al., 1996) as determined with either a SPAD or LCC at 7-10 day intervals on the most recent fully expanded leaves. About 20 to 45 kg N ha^{-1} is applied when the SPAD or LCC value falls below a critical threshold. The evaluation and use of the LCC to improve N management for rice in Asia has since 1998 been primarily through this 'real-time' N management approach. Real-time N management with the LCC has now been evaluated in numerous farmers' fields in south and Southeast Asia since 1998, when evaluation was started within the Crop and Resource Management Network

(CREMNET). However, this technique has not been adopted by Chinese farmers mainly because of labour shortage and relatively low profit of rice production.

Fertilizer P and K recommendations with SSNM are based on the indigenous supply of these nutrients from soil, organic materials, and irrigation water considering nutrient removal with grain and straw. Nutrient needs for micronutrients such as zinc and sulfur are based on local recommendations.

The Reaching Toward Optimal Productivity (RTOP) workgroup has collaborated with National Agriculture Research and Extension Systems (NARES) in eight Asian countries during Phase II (2001-2004) of the Irrigated Rice Research Consortium (IRRC) to systematically transform the initial SSNM concept into an inclusive framework for dynamic plant-need based management of N, P, and K. The framework of SSNM, which has emerged through RTOP across Asia, ensures that N, P, and K are applied as needed by the rice crop. SSNM eliminates wastage of fertilizer by preventing excessive rates of fertilization and by avoiding fertilization when the crop does not require nutrient inputs. It provides the fixed time-adjustable dose and real-time approaches as effective options for N management. It is compatible with integrated management of organic and inorganic nutrient sources, and it protects the environment by preventing excessive application of N fertilizer, which could leak from rice fields to contaminate water bodies and increase greenhouse gases in the atmosphere. Improved fertilizer management through SSNM can also reduce disease and insect damage in rice, thereby reducing the need for pesticides.

In the following, we present a summary of selected on-farm trials comparing SSNM with the farmers' fertilizer practice (FFP) in Jinhua, Zhejiang, to illustrate key findings of research conducted in 1998-2004. Based on these data, new fertilizer recommendations were developed for inbred and hybrid rice of the most common single- and double-rice cropping systems in Zhejiang.

2. Current nutrient management practice in Zhejiang Province

Zhejiang Province, located in the Southeaster China, belongs to the subtropical climatic zone with warm temperature (mean temperature 15-18 °C) and adequate rainfall (annual precipitation 1100-1900 mm). Research reports showed that the climate adjusted genetic yield potential of modern rice varieties currently grown in Zhejiang is about 10 to 12 t ha^{-1}. The yield potential is generally slightly lower in the early rice cropping season from April to July when inbred varieties are preferred compared to the late cropping season from July to October when higher yielding hybrid varieties are planted (Ten Berge et al., 1997). However, the current average double rice yield is only about 5.5 to 7.0 t ha^{-1} per season, which is only about 50 to 60% of the estimated yield potential for the modern rice varieties growing in this area. Chinese rice farmers have a long history of applying organic manure for rice. But now the situation has changed in Zhejiang. Rice farms nowadays can produce much less farmyard manure than before because they keep fewer animals due to farm mechanization. Also, farmers would rather like to use the small quantity of manure they produced for vegetable or other cash-making crops, not for the rice fields. Because of lacking labour and low profit, large quantities of organic manure produced in big animal farms (pig, chicken, and dairy farms) is usually wasted or not distributed evenly to the rice fields where it is needed. Straw is normally removed from the field after harvesting of the early rice crop. It often remains in the field after the late rice season but is commonly burned. Nowadays, much of the nutrient needs by rice are commonly provided with chemical fertilizer in Zhejiang.

Rice farmers in Zhejiang province usually apply about 18 kg ha^{-1} P per season as basal and 60 kg ha^{-1} K per season as basal or at early tillering growth stage. Research has shown that this P and K management strategy meets the rice requirement for P and K nutrition. Results of the long-term fertilization experiments indicate that soil P and K supply decreases within a short time (3-4 seasons for P and 1-2 seasons for K) so that yields decline, if fertilizer P or K are not applied (Wang et al., 2001c).

The environmental risk and wastage of fertilizer N and pesticide inputs are currently substantial in rice production systems in Zhejiang. Rice farmers in Zhejiang usually apply 150-250 kg ha^{-1} fertilizer N (with averages of 180 kg ha^{-1} for double rice crops and 240 kg ha^{-1} for single late rice crop) and 7-10 sprays of pesticides per season to maintain their relative high rice yield levels. About 85% to 100% of the total fertilizer N is used to promote tillering during the very early growth stage. Very few farmers apply N when the plant N demand is greatest in the middle of the season before or after panicle initiation. Thus N application is not fine-turned to synchronize supply and plant demand, which causes high rate of pesticide use and high N loses into the atmosphere and the water bodies. Although there is large variation in fertilizer applications and fertilizer use efficiency among the farms, fertilizer N use efficiency is generally very low. The apparent recovery efficiency of applied fertilizer N (REN) is usually lower than 20%, and the agronomy efficiency of fertilizer N (AEN, grain yield increase per unit fertilizer N) is always less than 10 kg kg^{-1} (Wang et al., 2004).

3. The agronomic performance of SSNM in farmers' fields in Zhejiang

3.1. Early trials in 1998-2000

The SSNM concept was first evaluated from 1997-2000 in Jinhua of Zhejiang, along with other seven sites in five Asian countries. To transfer SSNM concept into a new approach of fertilization practice, 21 individual farmers' fields distributed in seven townships in the double-rice cropping system of Jinhua were selected for the experiments. In the four seasons of 1997-1998, indigenous NPK supply was measured through nutrient omission plots (PK, NK, NP) in farmer's fields. The agronomic performance of SSNM has been tested against current farmer's fertilizer practice (FFP) from 1998-2000 in the farmer's fields. Grain yield, fertilizers (especially fertilizer N) use efficiency and profit were greater by SSNM than those achieved in FFP in both seasons and years despite significantly lesser use of fertilizer N, P and K (Table 1). More detailed analysis of the 1998-1999 data is shown in Table 2. As soil P and K supplies were not limiting plant growth and yield, as indicated by IPS and IKS measurements, the benefit of SSNM was mainly related to improved splitting and timing of fertilizer N applications leading to increased plant N, P and K uptake and to greater plant biomass production. This was particularly evident in 1999, when nutrient uptake, grain yield and profit were significantly greater in SSNM than in FFP although fertilizer N, P and K rates were all lower in SSNM, and the improved N strategy in SSNM resulted in an average saving of 61 kg fertilizer N ha^{-1} compared to the FFP. Across seasons and years, the average increase in plant nutrient accumulation due to SSNM was 7.7 kg N ha^{-1} (+8%), 2.4 kg P ha^{-1} (+14%), and 11.8 kg K ha^{-1} (+10%). These increases were significant. The corresponding significant yield increase due to SSNM was 0.45 t ha^{-1}. Note that SSNM performed equally well in both years although yields were considerably lower in 1999 due to unfavorable climatic conditions. SSNM performed equally well in the case of early rice (ER) and late rice (LR). Yields were highest in the 1998 LR crop, when the average yield by SSNM was 7.4 t ha^{-1}. Yields by SSNM exceeded 8 t ha^{-1} in five farms, where maximum was 8.7 t ha^{-1}. The average

Table 1. Comparison of SSNM with FFP (farmer's fertilizer practice) in double-rice cropping system in Jinhua from 1998 to 2000 (21 farms average).

	FFP	SSNM	SSNM-FFP
Rice yield (t ha^{-1})	6.0	6.4	0.4
Fertilizer N (kg ha^{-1})	170	120	–50
Fertilizer P (kg ha^{-1})	19.3	14.2	–5.2
Fertilizer K (kg ha^{-1})	58.2	51.9	–6.3
AEN (kg kg^{-1})	6.8	12.5	5.7
REN (kg kg^{-1})	18%	29%	11%
Profit (yuan ha^{-1})	6986	7716	730

Table 2. Effect of site-specific nutrient management on agronomic characteristics at Jinhua, Zhejiang Province, China (1998 - 1999).

		Treatment[b]					
	Levels	SSNM	FFP	? [c]	P>|T|[c]	Effects[d]	P>|F|[d]
Grain yield (GY)	All[a]	6.35	5.90	0.45	0.006	Village	0.003
(t ha^{-1})	Year-1	6.88	6.41	0.47	0.014	Crop-Year	0.679
	Year-2	5.82	5.40	0.43	0.046	-Season	0.269
	ER	5.80	5.41	0.39	0.056	-Year × Season	0.126
	LR	6.91	6.40	0.51	0.011	Village × Crop	0.049
Plant N uptake (UN)	All	105.9	98.2	7.7	0.003	Village	0.051
(kg ha^{-1})	Year-1	111.1	104.7	6.5	0.092	Crop-Year	0.505
	Year-2	100.6	91.7	8.9	0.004	-Season	0.707
	ER	103.5	96.1	7.4	0.040	-Year × Season	0.854
	LR	108.2	100.3	7.9	0.035	Village × Crop	0.832
Plant P uptake (UP)	All	20.9	18.4	2.4	0.002	Village	0.056
(kg ha^{-1})	Year-1	24.6	21.2	3.3	0.000	Crop-Year	0.003
	Year-2	17.2	15.7	1.5	0.052	-Season	0.156
	ER	19.7	17.5	2.1	0.027	-Year × Season	0.663
	LR	22.1	19.4	2.7	0.024	Village × Crop	0.054
Plant K uptake (UK)	All	130.3	118.5	11.8	0.014	Village	0.462
(kg ha^{-1})	Year-1	139.2	128.1	11.1	0.104	Crop-Year	0.968
	Year-2	121.4	108.9	12.4	0.043	-Season	0.667
	ER	116.1	105.9	10.2	0.093	-Year × Season	0.900
	LR	144.5	131.2	13.3	0.031	Village × Crop	0.213
Agronomic efficiency	All	11.4	6.3	5.0	0.000	Village	0.002
of N (AEN)	Year-1	10.8	7.2	3.7	0.000	Crop-Year	0.000
(kg grain kg N^{-1})	Year-2	11.9	5.5	6.4	0.000	-Season	0.063
	ER	10.2	5.8	4.3	0.000	-Year × Season	0.070
	LR	12.6	6.8	5.7	0.000	Village × Crop	0.050
Recovery efficiency	All	0.29	0.19	0.11	0.000	Village	0.004
of N (REN)	Year-1	0.27	0.22	0.06	0.031	Crop-Year	0.001
(kg N kg N^{-1})	Year-2	0.31	0.15	0.16	0.000	-Season	0.883
	ER	0.30	0.20	0.10	0.000	-Year × Season	0.957
	LR	0.28	0.17	0.11	0.000	Village × Crop	0.802

[a] All - all four crops grown from 98ER to 99LR; Year-1 -98ER and 98LR; Year-2 - 99ER and 99LR; ER - 98ER and 99ER; LR - 98LR and 99LR.

[b] FFP – farmers' fertilizer practice; SSNM - site specific nutrient management.

[c] ?= SSNM - FFP. P>|T| - probability of a significant mean difference between SSNM and FFP.

[d] Source of variation of analysis of variance of the difference between SSNM and FFP by farm; Prob>|F| = probability of a significant F-value.

profit increase in all four crops grown was US$ 93 ha^{-1} $crop^{-1}$ (+10%), but significantly larger in 1999 (US$ 112 ha^{-1} $crop^{-1}$, +14%) than in 1998 (US$ 75 ha^{-1} $crop^{-1}$, +8%). Compared to ER, farmers also achieved greater profit in LR because hybrid rice varieties with longer growth periods and higher yield potential were grown. The profit increase by SSNM over that in FFP was larger in the case of LR (US$ 108 ha^{-1} $crop^{-1}$) than in the case of ER (US$ 78 ha^{-1} $crop^{-1}$, 14%).

The N use efficiencies increased significantly with SSNM since plant N uptake and grain yield were greater despite lower N rates (Table 2). For all four crops grown, and compared to the FFP, AEN was increased by 5 kg kg^{-1} (+81%), REN by 0.11 kg kg^{-1} (+53%), and PFPN by 12.2 kg kg^{-1} (+34%). Differences in the impact of SSNM on N use efficiency in the case ER and LR were small. Nitrogen use efficiency was generally low in FFP, and also very variable among the farmers.

3.2. Modifications of SSNM in 2001-2004

We used field-specific recommendations in 1998-2000, but results indicated that improved, blanket recommendations with a 'fixed time-adjustable dose' N management strategy provided to a larger number of farmers rather than individual farmers would probably already result in yield and profit increases while improving N efficiencies. This hypothesis was tested in 2001-2004.

It is hypothesized that the critical factors influencing the need for improved field-specific NPK fertilizer recommendations for irrigated rice in a given season are:

- Yield potential as determined by variety and climate (solar radiation, temperature)
- Soil indigenous nutrient supply (soil type; parent materials; clay or sand content; soil organic matter (SOM); use of straw and organic manure; water source; grain yield in omission plots)
- Current yield level (5-year average)
- Current fertilizer use (5-year average)
- Cropping pattern-seasons
- Crop establishment method
- Crop management practice

Larger recommendation domains were developed based on above characteristics to achieve relatively homogenous areas with similar growing conditions for which a recommendation would be valid.

We validated characteristics of the recommendation domains by identifying 10-20 farmers' fields per domain where we implemented nutrient omission and fully fertilized plots to evaluate the domain with the following parameters measured in farmers' fields: Indigenous N, P and K supply measured as nutrient uptake and grain yield in the respective omission plots; yield response to fertilizer N, P and K application based on SSNM approaches; P and K soil analysis.

We then assumed an average attainable yield and nutrient requirement and used a generic fertilizer splitting pattern for the whole domain. Fertilizer P and K recommendations were based on the omission plot technique. As basal N application, 25% of the total N requirement was applied in all the fields of the domain. The remaining fertilizer N was applied in two to three splits at critical growth stages depending on plant growth and N requirement by growth stage, season, growth duration, and variety. Usually 30% of total N was given at early tillering and 35% of total N at PI, but rates were adjusted according to SPAD or LCC readings. A late season application of 10% of the total N was given at flower stage to improve grain filling, if the crop stand at that time was good with few pest problems.

The results of comparison between SSNM with FFP in the double cropping rice system in a pilot village of Tianmushan are shown in Table 3. SSNM increased rice yields by 0.4 t ha^{-1}, while fertilizer N was reduced by about 30% and AEN increased more than 50%. The more blanket approach to N management, i.e. guidelines that were developed for a larger number of farmers rather than individual farmers still resulted in yield and profit increases despite a simplification for the double-rice cropping system.

In Jiaxin, the most common cropping system is oil rape seed in rotation with single late rice. The high yielding single rice crop is typical for North Zhejiang with its high inputs. Soils are fertile and farmers apply 250-300 kg ha^{-1} of fertilizer N with 30% basal, 30% at early tillering, 25% at middle tillering, and 15% at PI. Rice yields of 7.5to 8.5 t ha^{-1} can be achieved. Fertilizer N use is very inefficient. Fertilizer P and K management is usually adequate, and major crop management problems are lacking. We conducted a set of field experiments with SSNM recommendations in one rice domain. With SSNM, total fertilizer N use was 150 kg N ha^{-1} with 25% basal, 30% at early tillering, about 35% at PI, and 10% at booting for some fields. Table 4 showed

Table 3. Comparison of SSNM with FFP in a pilot village of Tianmushan in Jinhua from 2001 to 2002 (20 farms average).

	FFP	SSNM	SSNM-FFP
Rice yield (t ha^{-1})	7.1	7.5	0.4
Fertilizer N (kg ha^{-1})	169	120	−49
N uptake (kg ha^{-1})	111	114	4
REN (%)	22	30	8
AEN (kg kg^{-1})	12.2	19.6	7.4

Table 4 Comparison of grain yield and fertilizer use efficiency between SSNM with FFP for single hybrid late rice in Jiaxing in 2004 (20 farms average).

	FFP	SSNM	SSNM-FFP
Rice yield (t ha^{-1})	8.44	8.98	0.54
Fertilizer N (kg ha^{-1})	301	152	−149
AEN (kg kg^{-1})	4.9	12.4	7.5

Table 5 Comparison of yield components between SSNM with FFP for single hybrid late rice in Jiaxing in 2004 (20 farms average)

	FFP	SSNM	SSNM-FFP	Increase (%)
No. of panicles m^{-2}	254	227	−27.00	−10.60
Percent filled spikelets	78.1	77.0	−1.10	−1.40
Total spikelets per panicle	164	201	37.00	22.60
Thousand grain weight (g)	22.1	22.1	0.00	0.00
Total dry matter yield (kgha^{-1})	17795	17868	73.00	0.40
Grain-straw ratio	0.85	0.94	0.09	10.60
Harvest index	0.440	0.462	0.02	5.00

that grain yield with SSNM increased by 0.5 t ha^{-1} compared to the FFP, while fertilizer N was reduced 50% and AEN increased by 150%. Table 5 shows that SSNM achieves less panicles m^{-2} but produced bigger panicles and higher grain-straw ratio explaining the yield increases over FFP. Again, the new SSNM approach to N management promised yield and profit increases for a larger number of farmers in the oil rape seed-single rice cropping systems.

4. Conclusion and discussion

There is great intensification and diversification of agricultural systems, which are competing for the limited natural resources especially for land and water with urban growth and industry development in China. From 1998 to 2003, annual rice production in China declined mainly due to decreasing rice area. Since rice-based cropping systems are the main food production systems in the South and Southeast of China, maintaining high rice yields and the sustainability of the rice ecosystem will always be a high priority to achieve food security in this country.

Different crop management practices by individual farmers resulted in great variation in soil fertility and productivity in Zhejiang Province as shown in the variations of grain yields and indigenous nutrient supply among the farmer's fields (Wang et al., 2004). However, blanket fertilizer recommendations are always given to the farmers by the government owned agricultural extension stations, which do not take into account the site-specific soil nutrient status. There is a large gap between the current rice yield and the potential yield in this studied area.

Farmers in major rice-growing areas of China over-apply N fertilizer to rice and it is evident they do not consider the often high indigenous N supply of the field when determining the amount of N to apply. There is significant potential to increase nitrogen use efficiency at the farm level. Our data showed that across seasons and years, compared with FFP, average grain yield increased about 0.5 t ha^{-1} under SSNM. The gross return over fertilizer cost was 10% greater with SSNM than with FFP. Improved timing and splitting of fertilizer N increased N recovery efficiency from 0.18 kg kg^{-1} in FFP plots to 0.29 kg kg^{-1} in SSNM plots. The agronomic N use efficiency was 80% greater with SSNM than with FFP. About 30 to 50% of fertilizer N used in current rice production could be reduced through adoption of SSNM, which could effectively reduce the unnecessary pollution with reactive nitrogen from rice fields (Wang et al., 2001b; Wang et al., 2004). Because of the substantial reduction of fertilizer N application at early growth stage with SSNM, less vegetative growth occurs early in the season improving micro-climate and canopy formation in SSNM plots. Less pesticides are needed because the rice crop is more healthy with SSNM, which reduces the risk of sheath blight disease.

SSNM was developed as a field-specific rather than site-specific nutrient management strategy considering the large variability of soil fertility even between neighboring rice fields. Since it is impossible to develop field-specific fertilizer recommendations for every farm in Zhejiang Province, SSNM recommendations were successfully simplified to be delivered in larger domains. Despite the large increases in N use efficiencies with SSNM, the recovery efficiency (REN) remained often below optimal targets of 50% and agronomy efficiency (AEN) remained often below 20 kg kg^{-1} indicating further room for improvements.

The major task now is to expand on-farm demonstration of improved N management technologies to all rice areas of Zhejiang to convince farmers, researchers, and governmental officials that yields, profit, and fertilizer N use efficiency can be easily improved through better timing of N applications so that fertilizer N use can be reduced.

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