



Performance of an Optimized Nutrient Management System for Double-Cropped Wheat-Maize Rotations in North-Central China

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ABSTRACT

Overapplication of N and P and insufficient supply of K are considered primary reasons for restriction of yield improvement in the North China Plain. Optimized nutrient management practices based on soil testing and yield targets have been developed. Other large scale field experiments have indicated that additional improvement for yield and nutrient use benefits is needed. The objective of this study was to evaluate the effects of the optimized nutrient management system on yield, nutrient uptake, nutrient utilization, and profit in the North China provinces of Shanxi, Hebei, Shandong, and Henan. Treatments consisted of a check without fertilizer use (CK); a balanced, optimum nutrient application (OPT); the farmers' practice (FP); and a series of nutrient omission treatments (minus N, P, and K, respectively). The results indicated that the OPT optimized grain yield, nutrient use efficiency, and profitability. Maize (*Zea mays* L.) yield increased by 12.2% at Shanxi and 18.5% at Hebei, respectively. Inputs of N and P across the wheat (*Triticum aestivum* L.) and maize system at the four sites was reduced by 13% (266 kg N ha⁻¹) and 45% (430 kg P₂O₅ ha⁻¹), while K input was increased by 43% (265 kg K₂O ha⁻¹). The OPT improved both measurements of nitrogen use efficiency (NUE); agronomic nitrogen efficiency (AE_N) and nitrogen recovery efficiency (RE_N) in the majority of cases. Although the OPT tested in this study increased yields and nutrient uptake, there remains considerable potential to improve AE_N and RE_N further for this intensive winter wheat–summer maize rotation system.

THE SINGLE-YEAR winter wheat-summer maize rotation is the most important agronomic crop production system in north-central China. Intensive fertilizer management commonly exposes this double-crop system to risks associated with unbalanced and excessive use of N fertilizer (Zhao, 2006). Excessive applications of N have prevailed in this region during the last two decades (Zhao, 1997; Gao et al., 1999; Chen, 2003). A recent investigation in the Shandong province showed the average application of N to summer maize to be 249 kg N ha⁻¹ as mineral fertilizer with an application range of 50–600 kg N ha⁻¹. This amount of N has been determined to exceed the crop requirements for maximum grain yield (Cui, 2005). The development and use of compound fertilizer products with a fixed nutrient ratio has resulted in imbalanced nutrient inputs. In 2005, the nutrient inputs from compound fertilizer comprised 24, 61, and 35% of total N, total P₂O₅, and

total K₂O input, respectively, and the ratio of N:P₂O₅:K₂O was 1:0.59:0.28 in Shandong (Ministry of Agriculture of China, 2007). An investigation in Shanxi indicated that the percentage of time that N application exceeded 250 kg N ha⁻¹ was 20% for wheat and 25% for maize, and the percentage of time that N application was <150 kg N ha⁻¹ was 56% for wheat and 53% for maize (Yang et al., 2008). Continuous winter wheat and summer maize cropping without balanced and efficient use of fertilizers has contributed to not only losses in yield and profit, but also to environmental problems such as groundwater nitrate-N contamination and eutrophication of rivers. A 1998 investigation of groundwater nitrate-N content in Shouguang County of Shandong province showed that 29% of 80 samples exceeded 45 mg NO₃⁻¹ L⁻¹. The percentage increased to 49% in 2001 (Chen et al., 2000; Zhu, 2002).

To overcome these nutrient management challenges, optimized nutrient management practices that are based on soil testing and yield targets have been developed to provide sustainable crop production and environmental protection. These optimized nutrient management practices originated from a systematic approach of evaluating soil fertility that dates back to the mid-1960s. Modified procedures of the systematic approach, as outlined by Hunter (1980, p. 42–44) and Portch and Hunter (2002), have been found useful for facilitating simultaneous evaluations of all essential mineral nutrients under rapidly changing and dynamic soil fertility environments (Rao et al., 2007). The most important treatment in this optimized nutrient management method is the *optimum fertilizer* treatment. This treatment is designed to bring the levels of all plant nutrients, and their ratios, to a status that

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Abbreviations: AE_N, agronomic nitrogen efficiency; CK, check without fertilizer use; FP, farmers' practice; INS, indigenous nitrogen supply; NUE, nitrogen use efficiency; OPT, optimum treatment; RE_N, nitrogen recovery efficiency.

overcomes whatever soil fertility problems that may exist while allowing maximum growth to occur. The other treatments in this methodology will test the status of an individual plant nutrient compared with the optimum. Thus, each treatment will be identical to the OPT, except for the exclusion of the one plant nutrient under study. The nutrient that is being studied will either be left out, or added, depending on whether it was left out or added to the optimum (Jin et al., 1996, p. 148–151; Portch and Hunter, 2002). This methodology was recently improved with the utilization of soil test and yield targets information. The recommendation derived via this method is then either verified or corrected using a series of crop responses studies (Jin et al., 2006, p. 148–151; Gao, 2008; Gao et al., 2008, 2009). The distinct feature of this optimized nutrient management approach is that it integrates soil test, target yield and crop responses to adjust nutrient recommendations. Large, field scale experiments have indicated that yield and profit can be improved with this optimized nutrient management approach (He and Wu, 2002; Ruan et al., 2005; Ye et al., 2006; Amarasekara et al., 2007; Gao et al., 2008, 2009; Gao, 2008; Wei et al., 2008). However, reports indicated that use of this methodology has been focused mostly on yield response and profitability improvement, and less on fertilizer use reductions and improvement in nutrient use efficiency. We hypothesized that optimized nutrient-balance management would (i) reduce N and P inputs in the areas where those nutrients have been overapplied; (ii) balance soil nutrient levels; and (iii) improve nutrient use efficiency. In this study, field experiments were conducted to evaluate this optimized nutrient management methodology for the commonly used wheat-maize rotation system in north-central China. The methodology was evaluated by analyzing yield, plant nutrient uptake, nutrient utilization, and profitability.

MATERIALS AND METHODS

Study Sites and Characterization for Optimum Nutrient Management

The field experiments included four locations where the rotation of winter wheat and summer maize was evaluated. The experiments were conducted in farmers' fields in Shanxi (111°26' E, 34°51' N), Hebei (115°12' E, 37°51' N), Henan (114°31' E, 35°71' N), and Shandong (121°08' E, 36°87' N for Haiyang and 120°26' E, 37°56' N for Laiyang, the two experimental sites were located very close and the wheat preceded the maize at Laiyang) provinces from 2006 to 2007. Winter wheat was sown at the beginning of October and harvested in mid June of the following year. Subsequent to the wheat

harvest, maize was immediately sown without tillage. Maize was harvested at the end of September, completing the winter wheat–summer maize annual rotation system.

Before each sowing, 15 to 20 randomly collected soil samples (from 0- to 20-cm depth) from each field were combined into one sample for each field. The nutrient status of each sample was determined using procedures applied by the National Laboratory of Soil Testing and Fertilizer Recommendation as described by Portch and Hunter (2002). The physical and chemical properties of the tested soils are shown in Table 1.

Each experiment used a randomized complete block design with six treatments and three replicates. The plot size ranged from 30 to 40 m², dependent on location. Treatments were comprised of a CK, a balanced OPT based on soil tests and target yield, the FP, and a series of nutrient omission treatments which excluded N, P, or K.

In the OPT treatment, the N amount was first determined based on soil organic matter (SOM) and crop target yield, and then modified using the soil mineral N (NO₃[−]-N + NH₄⁺-N) level. For P and K, the recommendation was based mainly on soil test level and crop target yield. All other nutrients besides N, P, and K were applied at the appropriate rate before sowing to eliminate possible limitations of yield. For example, 12 kg Zn ha^{−1} was applied to each crop at Shanxi, and at Henan, 12 kg Zn ha^{−1}, 50 kg S ha^{−1}, 20 kg Mn ha^{−1}, and 60 kg Fe ha^{−1} was applied to maize.

Urea, single superphosphate, and potassium chloride were used as the fertilizer sources. All fertilization application methods followed FP. The complete fertilizer application scheme is outlined in Table 2. All basal fertilizer applications were applied before sowing. Topdress applications were made by hand at Zadoks GS30 (Stapper, 2007) for winter wheat and at growth stage V10 (Ritchie et al., 1993) for maize. Crop planting and harvest details are given in Table 3. Irrigation, insect control, interrow tillage, and other management activities were conducted according to the FP.

Sampling, Measurements, and Data Analysis

At harvest, 3 m² (3 by 1 m) for wheat and about 15 m² (4 rows, 5 m in length) for maize from a location in the middle of each plot was harvested manually to determine straw and grain yield. Harvested straw and grain samples were oven-dried at 60°C for determination of dry matter weight. Subsamples of straw and grain were collected and analyzed for determination of N, P, and K concentration. For N concentration, the samples were digested using wet oxidation, and determined by micro-Kjeldahl distillation and titration. Plant tissue-P concentration was determined by vanadomolybdate yellow color

Table 1. Physical and chemical properties of tested soils in different locations of north-central China.

Location	Year	Soil type	pH	OM	K	NH ₄ ⁺ -N	NO ₃ [−] -N	P
				g kg ^{−1}		mg L ^{−1}		
Linfen, Shanxi	2006–2007	clacic cinnamon soils	8.1	3.5	72	3.1	20.5	21
Linfen, Shanxi	2007	clacic cinnamon soils	8.4	5.5	127	2.7	28.2	25
Xinji, Hebei	2006–2007	fluvo-aquic soils	8.4	7.0	78	4.9	28.0	22
Xinji, Hebei	2007	fluvo-aquic soils	8.3	7.8	71	5.8	11.8	45
Haiyang, Shandong	2006–2007	brown soils	4.4	12.0	45	8.9	8.5	59
Laiyang, Shandong	2007	brown soils	4.7	10.0	57	21.6	31.4	94
Xunxian, Henan	2006–2007	brown soils	7.7	11.6	99	25.1	22.0	21
Xunxian, Henan	2007	brown soils	7.9	8.6	77	29.6	15.8	20

Table 2. Fertilization rates of the optimum nutrient application (OPT) and farmers' practice (FP) treatments used at each experimental site.

Location	Rate of fertilizer application (N-P ₂ O ₅ -K ₂ O)			
	Wheat		Maize	
	OPT	FP	OPT	FP
	kg ha ⁻¹			
Shanxi	195-90-150	173-144-0	225-90-120	345-0-0
Hebei	180(30†)-100-75	300(30)-150-0	270(30)-45-120	160(30)-48-72
Shandong	240(60)-30-120	113(60)-113-113	150(50)-0-120	75(50)-75-75
Henan	210(50)-90-60(50)	360(50)-210-135(50)	240(50)-90-120(50)	450(50)-225-225(50)

† Data in parentheses indicate the percentage of fertilizer used as basal application, and data values without parentheses shown indicate fertilizers were used as 100% of basal application.

development. Plant tissue-K concentration was determined by flame spectrophotometers (Chinese Society of Soil Science, 2000). The total nutrient uptake of N, P, and K was calculated as the product of the nutrient concentration and plant dry weight. The indigenous supplies of nitrogen (INS), P, and K from the soil and other indigenous sources (Janssen et al., 1990) were estimated from total plant N accumulation at maturity in 0-N plots (INS), total plant P accumulation at maturity in 0-P plots, and total plant K accumulation at maturity in 0-K plots.

Nitrogen use efficiencies were estimated using the differences between the N-fertilized treatment and the 0-N plots per the procedure by Cassman et al. (1998). Efficiency terms used are apparent recovery efficiency of applied N (RE_N, kg N taken up kg⁻¹ N applied), and AE_N (kg grain yield increase kg⁻¹ N applied), which were calculated using Eq. [1] and [2]. RE_N is defined as the increase in crop N uptake by plant shoots in response to the application of the N, and AE_N is the product of the efficiency of N recovery from applied N fertilizer which was calculated in units of yield increase per unit of N applied.

$$RE_N = (U - U_0)/N \times 100 \quad [1]$$

$$AE_N = (Y - Y_0)/N \quad [2]$$

Where U and U₀ are crop N uptake in N-treated and 0-N plots, Y and Y₀ are grain yield in N-treated and 0-N plots, and N is the N rate.

Economic calculations were made using U.S. dollars as the standard currency:

$$TFC = P_N F_N + P_P F_P + P_K F_K \quad [3]$$

$$GRF = P_R Y_R - TFC \quad [4]$$

where TFC = total fertilizer cost (\$ ha⁻¹); P_N = price of N fertilizer; F_N = amount of N applied (kg N ha⁻¹); P_P = price of P fertilizer; F_P = amount of P applied (kg P₂O₅ ha⁻¹); P_K = price of K fertilizer; F_K = amount of K applied (kg K₂O ha⁻¹); GRF = the gross return above fertilizer cost (\$ ha⁻¹); P_R = price of wheat or maize; and Y_R = yield of wheat or maize (kg ha⁻¹).

The incremental profitability of OPT (ΔGRF, \$ ha⁻¹) was measured as the difference in GRFs due to the difference in grain yields for OPT and FP minus the change in total fertilizer costs due to the difference in fertilizer usage between the two treatments:

$$\Delta GRF = GRF_{OPT} - GRF_{FP} \quad [5]$$

Data were analyzed following ANOVA by SPSS 13.0 for Windows (SPSS, Inc., Chicago, IL). Treatment means were compared using least significant difference (LSD) at 0.05 level of probability whenever a significant *F* test was observed in the ANOVA.

RESULTS

Yields

Grain yield results (Table 4) revealed that yields of both wheat and maize in Henan were highest among the provinces. This site benefits from being situated within a highly productive zone where high inputs of fertilizer have been continually used and have resulted in higher levels of residual soil fertility. High yields within the unfertilized CK treatments (90% and 86% of those of OPT for wheat and maize, respectively), and a relatively small response to applied N in wheat and maize (<1 t ha⁻¹) further supports the high yield-potential rating for the Henan site. Yields at Shandong were lowest among the four sites. This was attributed to the excessive rainfall caused by a typhoon that impacted the site in 2007 and the low

Table 3. Schedule of crop planting and harvests in different provinces of north-central China.

Province	Year	Crop/cultivar	Seeding rate	Seeding date	Harvest date
Shanxi	2006-2007	Wheat/Jinmai 81	225 kg ha ⁻¹	8 Oct. 2006	12 June 2007
	2007	Maize/Zhengdan 958	57,600 plants ha ⁻¹	12 June 2006	16 Oct. 2007
Hebei	2006-2007	Wheat/Shimai 17	225 kg ha ⁻¹	12 Oct. 2006	10 June 2007
	2007	Maize/Zhengdan 958	63,000 plants ha ⁻¹	17 June 2007	9 Oct. 2007
Shandong	2006-2007	Wheat/Jinan 17	225 kg ha ⁻¹	12 Oct. 2006	19 June 2007
	2007	Maize/Zhengdan 958	60,000 plants ha ⁻¹	23 June 2007	10 Oct. 2007
Henan	2006-2007	Wheat/ZM98165	150 kg ha ⁻¹	14 Oct. 2006	5 June 2007
	2007	Maize/Zhengdan 958	75,000 plants ha ⁻¹	12 June 2007	3 Oct. 2007

Table 4. Grain yield in different nutrient management plots at each experiment site.

Treatment†	Shanxi		Hebei		Shandong		Henan	
	Wheat	Maize	Wheat	Maize	Wheat	Maize	Wheat	Maize
t ha ⁻¹								
OPT	6.7 a‡	8.3 a	5.8 a	7.7 a	6.2 a	5.0 a	7.7 a	10.4 a
OPT-N	5.8 b	6.3 c	4.8 b	6.7 b	4.3 c	3.7 c	7.0 c	9.6 b
OPT-P	6.2 ab	7.9 ab	4.9 b	6.9 b	3.9 c	4.4 b	7.3 bc	9.6 b
OPT-K	6.2 ab	8.2 a	5.0 b	6.8 b	5.0 b	4.6 ab	7.2 c	9.7 b
FP	6.2 ab	7.4 b	5.1 ab	6.5 b	5.9 a	4.8 a	7.6 ab	9.8 a
CK	5.7 b	5.6 d	3.7 c	6.4 b	3.9 c	4.5 b	6.9 c	8.9 c

† OPT, the optimum nutrient application treatment; OPT-N, nitrogen omission treatment; OPT-P, phosphorous omission treatment; OPT-K, potassium omission treatment; FP, the farmers' practice; CK, the check treatment without fertilizer use.

‡ Different letters after a yield value for a crop at a location indicate significance of treatment differences at that location ($P < 0.05$).

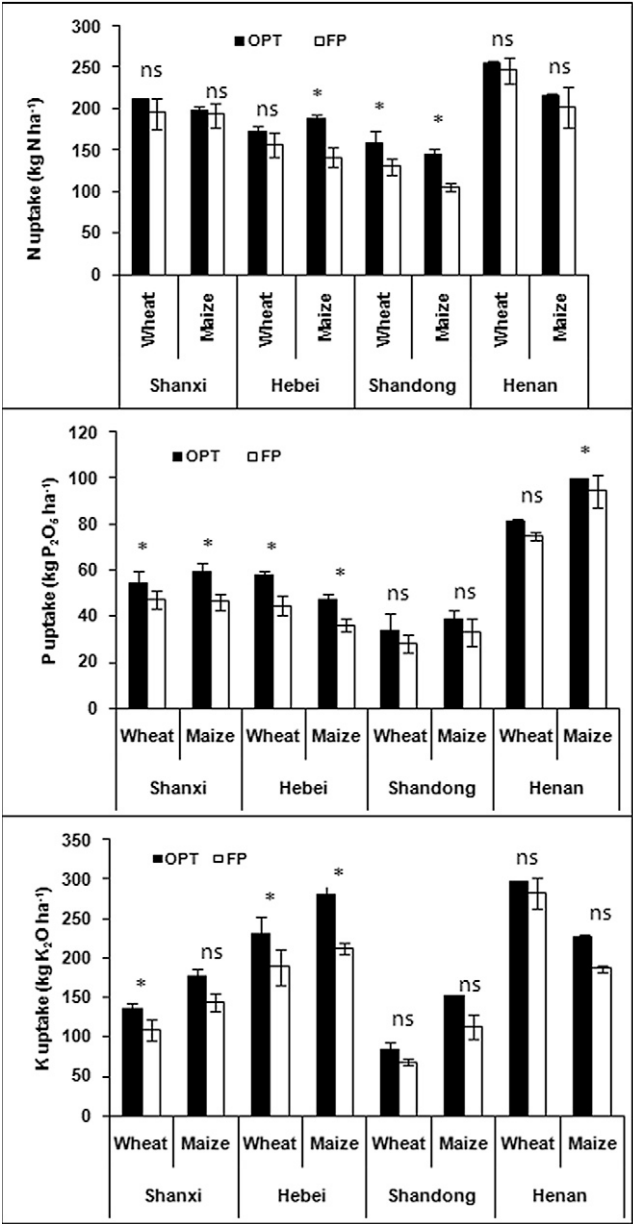


Fig. 1. Nutrient uptake with optimum nutrient application (OPT) and farmers' practice (FP) at four sites in north-central China. Bars indicate the means and error bars indicate the standard error of the means across replicates ($n = 3$). The symbol * and ns label above individual columns indicate significance at $P < 0.05$ and no significant difference between OPT and FP, respectively, with t test analysis.

soil fertility associated with the brown soils that are prevalent to this location (Fig. 1).

Yields among fertilizer treatments for both wheat and maize varied at each of the sites and significant differences among the treatments were observed (Table 4). In all cases, a response to N was observed indicating it was generally the most limiting nutrient at each of the sites. At three of four sites (Shanxi was the exception) a yield response also was observed for P and K. The OPT treatment significantly increased maize yields by 12.2 and 18.5% compared with the FP in Shanxi and Hebei, respectively. However, maize yields under the OPT treatments in Shandong and Henan were not different than those observed in the FP treatment. For winter wheat, the OPT treatment was unable to increase grain yields beyond those obtained with the FP at any of the sites (Table 4). Although the fertilizer application regime was different at each of the sites due to different local FP, a common problem among the sites was an imbalanced use of nutrients (Table 2); for example, N overapplication in maize and no K for either crop at Shanxi; N overapplication and no K in wheat and less than required N and K in maize at Hebei; and at Shandong, an equal ratio of $N-P_2O_5-K_2O$ was used based on the compound fertilizer product applied. At Henan, high yields were attained with the FP but they were realized with excessive nutrient inputs (Table 2). Although the total nutrients applied at Henan using the FP almost doubled those for the OPT, no yield differences for wheat and maize were observed (Table 4), resulting in fertilizer waste, low nutrient use efficiency, and major profit losses using the FP rates.

By adoption of the OPT nutrient management strategy, the total nutrient input to the whole wheat and maize system across the four sites was reduced by 13% (266 kg N ha^{-1}) for N and 45% ($430 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$) for P, and was increased by 43% ($265 \text{ kg K}_2\text{O ha}^{-1}$) for K (Table 2).

Nutrient Uptake and Utilization

Nutrient uptake followed trends similar to those observed for yields. The OPT treatment achieved the highest value in each crop followed by FP (Fig. 1). For most cases, the OPT treatment with the higher amount of nutrient input brought about higher nutrient uptake, and the OPT with the lower nutrient input didn't reduce nutrient uptake compared with the FP; for example, the OPT at Shandong with applications of 240 kg N ha^{-1} for wheat and 150 kg N ha^{-1} for maize achieved higher N uptake than the FP with applications of 113 kg N ha^{-1} for wheat and 75 kg N ha^{-1} for maize. Another

example occurred at Henan, where the OPT reduced the amount of fertilizer N and P used by large amounts, but there was no reduction in N and P uptake cause by this reduction. Additionally at Henan, K rate was reduced by >50% without a loss of K uptake by both crops (Fig. 1). These results indicated that the FP of either imbalanced or overuse of nutrient inputs did not result in increased nutrient uptake.

The indigenous nutrient supply refers to all nutrients from soil and environmental sources. It can be defined as the cumulative quantity of nutrients from all nonfertilizer sources that are found in the soil solution surrounding the root system during one complete crop cycle (Janssen et al., 1990). For example, components of INS include soil organic matter, residual organic and inorganic N from previous N applications, atmospheric N fixed by legumes and free-living N-fixing bacteria, and atmospheric deposition (Legg and Meisinger, 1982). In this experiment, the mean INS (Table 5) for wheat was 136.2 kg ha⁻¹ (range 100.9–185.1 kg ha⁻¹; 63.3–72.8% of total aboveground N uptake) and for maize 130.8 kg ha⁻¹ (97.1–166.5 kg ha⁻¹; 58.8–77.5% of total aboveground N uptake). The ranking of sites for INS in the wheat and maize rotation system was Henan > Shanxi > Hebei > Shandong, a ranking of sites which showed a similar trend to that of the yields. Indigenous P supply for wheat was 43.7 kg P₂O₅ ha⁻¹ (18.7–67.8 kg P₂O₅ ha⁻¹; 63.2–89.4% of total aboveground P₂O₅ uptake) and for maize 51.2 kg P₂O₅ ha⁻¹ (18.7–67.8 kg P₂O₅ ha⁻¹; 58.8–77.5% of total aboveground P₂O₅ uptake). Indigenous K supply for wheat was 154.0 kg K₂O ha⁻¹ (46.5–262.6 kg K₂O ha⁻¹; 68.4–98.0% of total aboveground K₂O uptake) and for maize 158.8 kg K₂O ha⁻¹ (88.8–246.3 kg K₂O ha⁻¹; 71.6–91.5% of total aboveground K₂O uptake). These indigenous nutrient supply results indicated that the supply of N, P, and K from the soil and other nonfertilizer sources was relatively high, a point supported by the relatively low yield responses with the omission treatments of N, P, and K to the OPT nutrient applications (<1 t ha⁻¹ in most cases) (Table 4). However, a significant yield increase with the OPT compared with the CK was observed in every case, and in every case except two, there was a yield increase realized with the FP compared with the CK. Moreover, the OPT produced the same or better yield with improved (more balanced) nutrient applications than occurred with FP, which demonstrated that the addition of OPT nutrients provided a yield benefit although

Table 5. Indigenous nutrient supply in different provinces of north-central China.†

Indigenous nutrient supply‡	Wheat	Maize	Wheat	Maize
	kg ha ⁻¹			
	Shanxi		Hebei	
INS	144.0 ± 5.4	116.0 ± 3.6	114.7 ± 19.4	143.7 ± 9.0
IPS	45.1 ± 2.6	44.7 ± 7.5	43.1 ± 4.8	40.1 ± 1.5
IKS	105.8 ± 6.4	149.5 ± 11.3	201.2 ± 20.4	246.3 ± 8.2
	Shandong		Henan	
INS	100.9 ± 11.1	97.1 ± 9.6	185.1 ± 15.0	166.5 ± 2.1
IPS	18.7 ± 3.9	33.0 ± 5.8	67.8 ± 2.0	87.2 ± 3.5
IKS	46.5 ± 1.9	88.8 ± 4.2	262.6 ± 5.8	183.6 ± 5.4

† Values shown are means ± SD (n = 3).

‡ INS, IPS, and IKS indicate indigenous N, P, and K nutrient supply, respectively.

the indigenous nutrient supplies were fairly high. This clearly showed that over fertilization was occurring with the FP and that utilization of the soil test information that the OPT was based on could help reduce nutrient inputs.

Nutrient use efficiency can be expressed as both agronomic efficiency (AE) and crop recovery efficiency (RE) (Dobermann, 2007; Fixen, 2007). Agronomic efficiency refers to the crop yield increase per unit nutrient applied, and RE refers to the increase in plant nutrient uptake per unit nutrient applied. Since N was found to be a limiting nutrient for yield for both crops at all the locations (Table 4), our discussion highlighted the AE_N and RE_N. Although the differences in AE_N in most cases and RE_N in some cases were not significant, the OPT treatment showed trends toward improvement in N use efficiency. For example, both AE_N and RE_N for the OPT treatment at Henan doubled in comparison to those for the FP although the FP at this location had very high nutrient input (Table 2). In most cases, it was demonstrated that the FP with either imbalanced or excessive use of nutrients was unable to attain either higher yield or improved N uptake per unit of N applied (Table 6).

Crop Profitability

Crop profitability mirrored the yield responses with the OPT treatment being either similar or more cost-effective than the FP treatment (Fig. 2). The mean net returns of OPT over FP for the rotation system of wheat and maize for each of the

Table 6. Nitrogen use efficiency of the optimum nutrient application (OPT) and farmers' practice (FP) in different provinces of north-central China.

Location	Crop	AE _N †			RE _N		
		OPT	Significance	FP	OPT	Significance	FP
		kg kg ⁻¹			%		
Hebei	maize	8.9 ± 1.5‡	ns§	5.1 ± 3.0	35.5 ± 1.3	*	15.7 ± 3.8
	wheat	5.6 ± 3.2	ns	1.3 ± 1.0	32.3 ± 8.8	*	10.7 ± 2.0
	maize	3.9 ± 1.0	*	1.8 ± 1.0	18.0 ± 2.2	ns	14.7 ± 5.1
Shandong	wheat	7.9 ± 2.5	ns	14.1 ± 3.5	24.9 ± 4.2	ns	23.7 ± 7.1
	maize	8.5 ± 1.8	*	13.4 ± 5.2	34.2 ± 4.8	*	17.0 ± 1.7
Henan	wheat	3.2 ± 1.2	ns	1.7 ± 1.1	33.0 ± 5.1	*	15.8 ± 10.1
	maize	3.2 ± 2.1	*	1.2 ± 0.5	20.1 ± 1.7	*	7.4 ± 0.9

* Nutrient use efficiency between OPT and FP is significant at P < 0.05.

‡ Values shown are means ± SD (n = 3).

† AE_N, agronomic efficiency of N; RE_N, recovery efficiency of N.

§ ns, nutrient use efficiency between OPT and FP is not significant at P < 0.05.

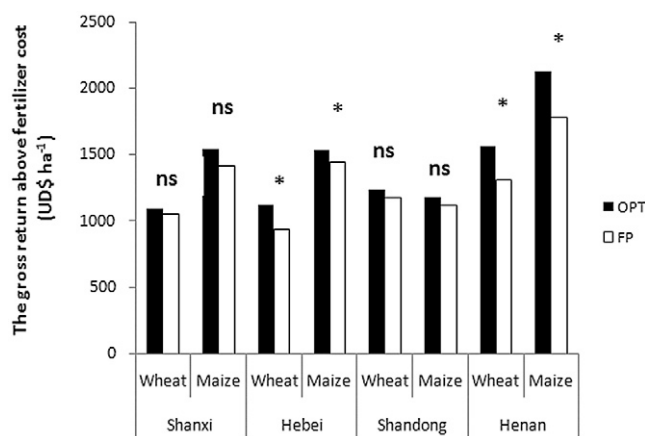


Fig. 2. The mean gross return above fertilizer cost with optimum nutrient application (OPT) and farmers' practice (FP) at four sites in north-central China ($n = 3$). The symbol * and ns label above individual columns indicate significance at $P < 0.05$ and no significant difference between OPT and FP, respectively, with t test analysis. The crop product values and fertilizer prices at the time of the experiment (2006–2007) = 3.4–3.9 RMB kg^{-1} N, 4.4–4.6 RMB kg^{-1} P_2O_5 , and 3.4–4.3 RMB kg^{-1} K_2O , 1.4–1.6 RMB kg^{-1} wheat, and 1.5–1.8 RMB kg^{-1} maize; exchange rate: 1 US\$ = 6.9 RMB.

locations were US\$ 170 ha^{-1} (6.9%), US\$ 279 ha^{-1} (11.7%), US\$ 123 ha^{-1} (5.4%) and US\$ 599 ha^{-1} (19.4%) for Shanxi, Hebei, Shandong, and Henan, respectively. Greater profits were attained planting maize compared with the profits realized for planting wheat. It is deserving to mention here that the OPT obtained a higher net profit at Henan primarily because of the reductions in N (44%), P (59%), and K (49%) use.

DISCUSSION AND CONCLUSIONS

Imbalanced nutrient applications and overapplication of N and P have presented a great challenge to north-central China in recent years. These practices have resulted in losses of yield and profits for farmers, and caused detrimental environmental effects that require urgent responses to reverse their current direction (Chen et al., 2000; Zhu, 2002; Zhao, 2006). In this study, the improved nutrient management attained with the OPT treatment increased yield and profit by reducing fertilizer N and P inputs and improving nutrient use efficiency in most cases. Therefore, using an optimum fertilizer application approach proved to be beneficial for nutrient management. However, compared with developed countries, the nutrient use efficiency for this region of China is still very low. Dobermann (2007) reported that AE_N and RE_N for cereals in developing countries ranged between 10 and 30 kg kg^{-1} and 30–50%, respectively. But, they also indicated that nutrient use efficiency could reach an average value $> 25 \text{ kg kg}^{-1}$ (AE_N) and 50–80% (RE_N) in a well-managed system; in a system with low levels of N use; or in a system with low soil N supply. In our study, most AE_N values were $< 10 \text{ kg kg}^{-1}$, and RE_N values were $< 35\%$. This is attributed to continuous use of high N inputs and an imbalanced use of P and K in recent years in north-central China (Zhao, 1997; Gao et al., 1999; Chen, 2003; Cui, 2005). This outcome was in accordance with the lower NUE caused by increased N use that was reported by Dobermann (2007) for developing countries. Further analyses demonstrated that negative linear correlations existed between AE_N , RE_N , and

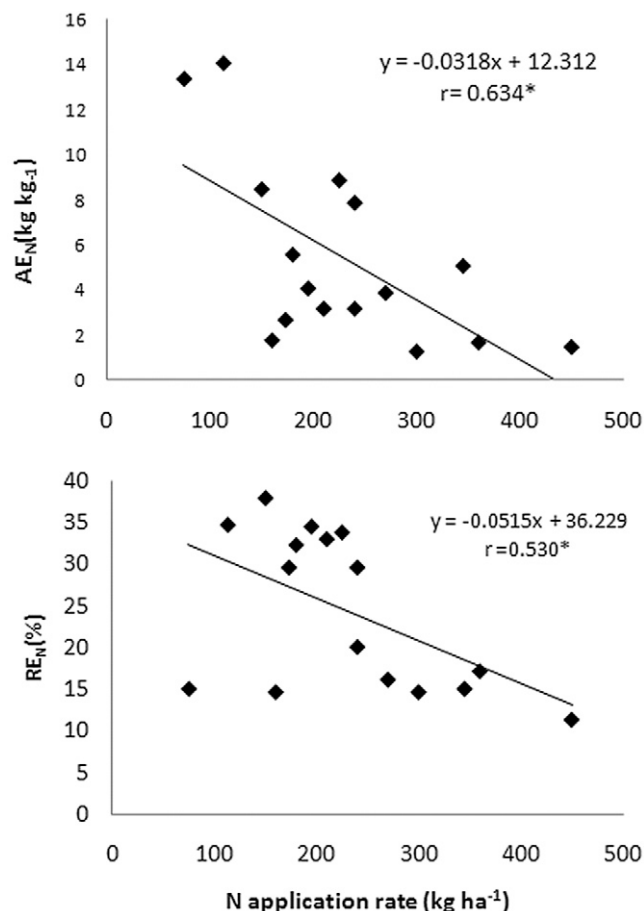


Fig. 3. Correlation between agronomic efficiency of nitrogen (AE_N), recovery efficiency of nitrogen (RE_N), and nitrogen application rate in north-central China. Each linear correlation fitting produced a significant model ($P < 0.05$).

N application rate (Fig. 3). A higher AE_N was observed for both wheat and maize for FP treatment in Shandong due to the lower N rate used compared with the OPT treatment. It was indicated that the higher AE_N or RE_N could be reached either by lowered N application rate in the N overuse areas, or by improved N management practices. Since it was quite simple to reduce the N application rate in N overuse areas, it was more important to optimize N management to improve N use efficiency. The low NUE observed in the current study means that additional in-season N management strategies, such as using a chlorophyll meter or leaf color chart in rice (*Oryza sativa* L.) (Peng et al., 1993, 1995, 1996; Peng and Cassman, 1998; Shukla et al., 2004), may assist in attaining more improvement but little information is available about these techniques for the wheat–maize rotation system. Therefore, designing an N management strategy that involves a combination of anticipatory (N applied as a basal dressing at the beginning of the growing season based on available soil information and an expected target yield) and reactive (in-season N top dressing during the growing season guided by a chlorophyll meter or leaf color chart) decisions (Dobermann and Cassman, 2002) will improve the performance of nutrient management by accounting for seasonal variation and therefore matching crop need with nutrient supply. Specific algorithms for in-season prescription of N based on crop diagnostics tools have to be

evaluated more rigorously. This is because crop greenness can only be sensed reliably after about the V6 growth stage of maize and because crop greenness is also affected by factors other than N. It should also be noted that yield potential in maize is, to a large degree, determined by factors such as solar radiation, temperature, moisture, and nutrient supply during grain filling, that is, long after most of the N has been applied (Yang et al., 2006). Hence, for optimal performance, reactive N management should be integrated with predictive algorithms that aim at preventing deficiencies or excess of N at the critical stages for yield component formation.

The indigenous nutrient supply was successfully used in recent studies of site-specific nitrogen management (SSNM) of irrigated rice (Wang et al., 2001; Dobermann et al., 2002) and maize (Schmitt et al., 1998; Hoefst and Peck, 2001). However, INS and site-specific nitrogen management have rarely been reported for wheat and maize. Dobermann et al. (2003) demonstrated that NUE could be increased without any basal N application at planting for both rice and wheat crops provided that INS is sufficiently high (50–60 kg N ha⁻¹ for rice and 35–45 kg N ha⁻¹ for wheat). The INS for wheat in our study averaged >136 kg N ha⁻¹, a value that is almost three times that reported in the study by Dobermann et al. (2003). Nitrogen use efficiency could also be improved if a basal N application is no longer needed because of high INS, a characteristic that was prevalent in our study conducted in the highly intensive wheat-maize rotation area of north-central China. It could also be interpreted that indigenous nutrient supply could be a supplemental tool used to verify the crop responses to the soil-test based recommendations, and finally used to modify the optimized nutrient management approach that is based on a soil test.

More importantly, because yield potential and nutrient availability are determined by many other factors in addition to nutrients, the best nutrient management strategies must be integrated with other agronomic best management practices. These practices may include investment in high-yielding cultivars with stress tolerance, use of better soil and crop management technologies, and implementation of practices learned through extension education. In addition, mandatory regulation of excessive N or P use by both the public and the private sector to increase nutrient use efficiency may also be implemented as has been done in many developed countries (Cassman et al., 2002; International Fertilizer Industry Association, 2007; Ping et al., 2008).

In summary, the improved nutrient management based on soil testing and a crop target yield, that is, OPT treatment plots used in this study, demonstrated promising agronomic and economic potential. The OPT treatment increased yield and profit by reducing N and P inputs and improving nutrient use efficiency in most cases. However, there remains additional potential for increasing yields and for improving resource use efficiency and profitability with the integration of both anticipatory and reactive in-season N management.

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