Title
Nutrient uptake and utilization of nutrient management for wheat and maize rotation system in North Central China

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Introduction

The single-year winter wheat–summer maize rotation is the most important agricultural production system in North Central China. High cropping intensity commonly exposes this double-crop system to risks associated with unbalanced and excessive use of nitrogen (N) fertilizer (Zhao et al., 2006). Excessive application of N has prevailed in this region over the last two decades (Zhao, 1997; 1999; Chen, 2003; Cui, 2005; Yang et al., 2008). To overcome these challenges and guarantee food security in China, optimized nutrient management practices based on soil testing and target yield have been developed for sustainable crop production and environmental protection. We hypothesized that improved nutrient-balance management will reduce N and phosphorus (P) input in the N and P over-application area, balance soil nutrient levels and improve nutrient use efficiency. In this study field experiments were conducted in North Central China and to determine yield and nutrient use efficiency benefits of implementing an improved nutrient management system that is soil test-based and balanced with respect to relative quantities of N, P and K fertilizers.

Materials and methods

The field experiments included four winter wheat and four summer maize experiments, which 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) 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 and harvested at the end of September, which represented the typical winter wheat–summer maize rotation system.

Prior to each sowing, soil samples (from 0 to 20 cm depth) were collected and the nutrient status of each sample was analyzed. Soil nutrients were determined with procedures applied by the National Laboratory of Soil Testing and Fertilizer Recommendation as described by Porch and Hunter (2002). The physical and chemical properties of the tested soils are given in Table 1.

Each experiment was designed in a randomized complete block with six treatments and three replicates. Treatments comprised a check without fertilizer use (CK), a balanced 'optimum' nutrient application (OPT) based on soil tests and target yield, and a series of nutrient omission treatments consisting of OPT-N, OPT-P, OPT-K, and farmers' practice (FP). Urea, single super phosphate, and potassium chloride were selected as fertilizer sources. All other limiting nutrients in addition to N, P and K were applied at a proper rate before sowing for all treatments to eliminate possible limitation of yield.

All fertilization methods followed farmers' practices. The complete fertilizer application scheme is outlined in Table 2. Irrigation, insect control, inter-row tillage and other management activities were conducted according to farmers' practice. At harvest stage, 3 m^2 (3 m×1 m) for wheat and about 15 m^2 (4 row×5 m in length) for maize from a location in the middle of each plot was harvested manually to determine straw and gain 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.

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

Nitrogen use efficiencies were estimated using the differences between the N-fertilized treatment and the 0-N plots, as described by Cassman et al. (1998). Terms used are agronomic efficiency of applied N (AE_N, kg grain yield increase kg^{-1} N applied), apparent recovery efficiency of applied N (RE_N, kg N taken up kg^{-1} N applied), and partial factor productivity of applied N (PFP_N, kg grain kg^{-1} N applied).

The differences among the treatments were analyzed using analysis of variance (ANOVA). Statistical analyses were performed using DUNCAN procedures of SPSS 13.0 for Windows (SPSS, Inc.).

Table 2 Fertilizer treatment design for wheat and maize in different provinces of North Central China

Province	Treatments	Wheat			Maize		
		Nutrient application (kg ha^{-1})					
		N	P_2O_5	K_2O	N	P_2O_5	K_2O
Shanxi	OPT	195	90	150	225	90	120
	FP	173	144	0	345	0	0
Hebei	OPT	180	100	75	270	45	120
	FP	300	150	0	160	48	72
Shandong	OPT	240	30	120	150	0	120
	FP	113	113	113	75	75	75
Henan	OPT	210	90	60	240	90	120
	FP	360	210	135	450	225	225

Results

Crop yield comparisons across sites indicated that yields in Shanxi and Hebei were higher than those in Shandong, where yields were severely limited by low pH and low soil fertility, especially low K in brown soils (Fig. 1). Yields of both wheat and maize in Henan were highest among the provinces as this site benefits from being situated within a highly productive zone having continuous and high input of fertilizers and therefore higher residual soil fertility. High yields within the unfertilized check treatments, and a relatively small response to applied N in wheat (773 kg ha ^{1}) and maize (895 kg ha ^{1}) further supports the high yield-potential ranking for the Henan site.

Nitrogen was generally the most limiting factor for the wheat–maize system in all provinces, followed by P and K. As compared with the FP treatment, the OPT treatment significantly increased maize yields by 12.2% and 18.5% in Shanxi and Hebei, respectively. However, maize yields under the OPT treatments in Shandong and Henan were not statistically better than those in the FP treatment, and the set of OPT treatments were unable to significantly increase winter wheat yields beyond those obtained under FP at any of the sites. Although the fertilizer application regime was different in the four sites due to different local farmers' practices, imbalanced nutrient input was the common problem in this region; for example, N over-application in maize and no K input in both crops in Shanxi; N over-application and no K in wheat and less K in maize in Hebei; and equal ratio of $N:P_2O_5: K_2O$ input due to the equal ratio of $N:P_2O_5: K_2O$ in the compound fertilizer used, resulting in less nutrient input and lower yield in both crops in Shandong. At Henan, high yields were attained with the FP but they were ealized with excessive nutrient inputs. 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 at Henan, resulting in fertilizer waste, low nutrient use efficiency and major profit losses with the use of FP.

By adoption of the OPT nutrient management strategy, the total nutrient inputs to the whole wheat and maize system at four sites was reduced by 13% (266 kg N ha^{-1}) for N and 45% (430 kg P_2O_5 ha^{-1}) for P, and K input was increased by 43% (265 kg K_2O ha^{-1}) for K (Fig. 1).

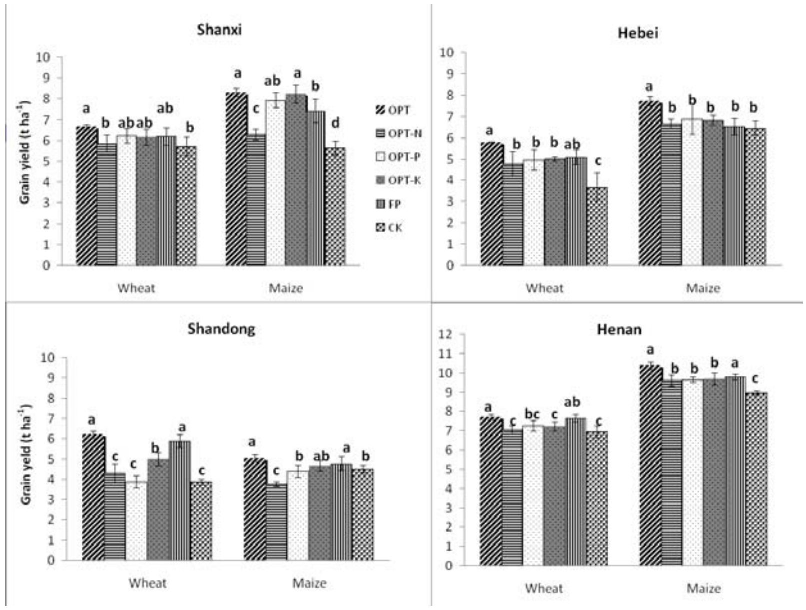

Fig.1 Grain yield in different nutrient management plots at four sites in North Central China. Bars indicate the mean values and error bars indicate the standard errors. Different letters indicate a significant difference exists among treatments ($P < 0.05$).

Nutrient uptake followed trends similar to those observed for yields. The OPT treatment achieved the highest value in each crop followed by FP (Fig. 2). In comparison with FP, the OPT increased N uptake by 2.9–22.0% (7.2–28.7 kg N ha^{-1}) for wheat and 2.0–37.7% (3.9–45.7 kg ha^{-1}) for maize, increased P uptake by 8.3–30.0% (5.7–13.4 kg P_2O_5 ha^{-1}) for wheat and 4.8–31.0% (4.5–12.8 kg P_2O_5 ha^{-1}) for maize, and increased K uptake by 5.1–25.6% (14.3–40.8 kg K_2O ha^{-1}) for wheat and 21.3–37.1% (34.0–68.5 kg K_2O ha^{-1}) for maize, respectively (Fig. 2).

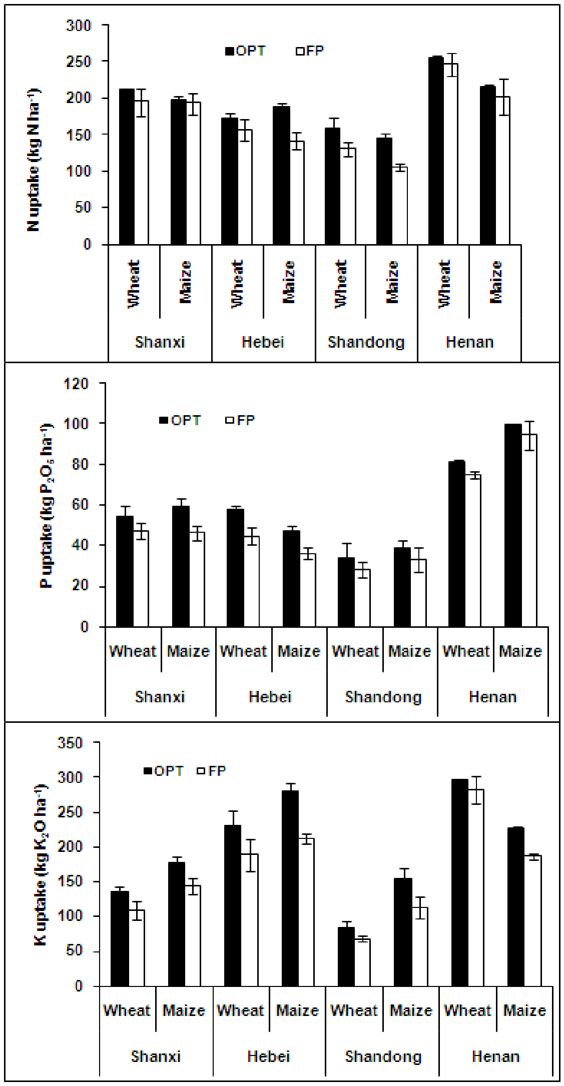

Fig. 2. Nutrient uptake with optimum nutrient application (OPT) and farmers' practice (FP) at four sites in North Central China. Bars indicate the means and error bars indicate the standard errors (*n* = 3).

Nutrient use efficiency can be expressed as partial factor productivity (PFP), agronomic efficiency (AE), and crop recovery efficiency (RE) (Dobermann, 2007; Fixen, 2007). PFP refers to the crop yield per unit nutrient applied, AE refers to the crop yield increase per unit nutrient applied, and RE refers to the increase in plant nutrient uptake per unit nutrient applied. In comparison with FP, measurements of PFP_N under OPT treatment increased in Henan and decreased in Shandong because a lower amount of N was applied in Henan and a higher amount of N was applied in Shandong with OPT. PFP_N varied between the crops in Shanxi and Hebei based on different nutrient applications. OPT treatments in all four sites achieved higher AE_N and RE_N than FP except in Shandong (lower AE_N with OPT treatment due to the higher rate of N applied), indicating that optimal nutrient management could improve nitrogen use efficiency (Table 3).

Table 3 Nutrient use efficiency of N, P_2O_5 and K_2O in different provinces of North Central China[a]

Nutrient		Shanxi		Hebei		Shandong		Henan		Mean	
		Wheat	Maize	Wheat	Maize	Wheat	Maize	Wheat	Maize	Wheat	Maize
PFP_N ($kg\ kg^{-1}$)	OPT	34.1	36.9	32.1	28.6	25.8	33.5	41.7	43.2	33.4	35.6
	FP	35.9	21.5	16.8	43.4	52.3	63.4	24.7	22.5	32.4	37.7
AE_N ($kg\ kg^{-1}$)	OPT	4.1	8.9	5.	3.9	7.9	8.5	3.2	3.2	5.2	6.1
	FP	2.7	5.1	1.3	1.8	14.1	13.4	1.7	1.5	5.0	5.5
AE_P ($kg\ kg^{-1}$)	OPT	6.7	5.3	8.2	18.8	78.1	nd	5.0	8.2	24.5	10.8
AE_K ($kg\ kg^{-1}$)	OPT	4.2	3.2	10.2	7.5	10.2	3.2	8.0	5.8	8.2	4.9
RE_N (%)	OPT	34.5	33.8	32.3	16.2	24.2	32.2	33.0	20.1	31.0	25.6
	FP	29.0	15.1	14.7	14.7	16.1	11.4	17.2	11.4	19.3	13.1
RE_p (%)	OPT	13.7	16.1	15.1	16.3	36.7	nd	14.7	13.4	20.1	15.3
RE_k (%)	OPT	20.7	23.6	38.3	28.9	31.4	55.0	57.9	35.8	37.1	35.8

[a] Values shown are means (n = 3). nd, no data available; PFP_N, partial factor productivity of N; AE_N, AE_P, AE_K, agronomic efficiency of N, P and K, respectively; RE_N, RE_P, RE_K, recovery efficiency of N, P and K, respectively.

AE and RE for applied N, P and K under OPT treatment resulted in large between-crop and among-location variability. Mean AE values were 5.2 kg N kg^{-1}, 24.5 kg P_2O_5 $kg^{-1}$and 8.2 kg K_2O kg^{-1} for wheat, and 6.1 kg N kg^{-1}, 10.8 kg P_2O_5 kg^{-1} and 4.9 kg K_2O kg^{-1} for maize, respectively. The higher AE value of 78.1 kg kg^{-1} P_2O_5 resulted from the lower P_2O_5 application rate (30 kg P_2O_5 kg^{-1}) for winter wheat in Shandong province. The mean RE values of N, P and K for the first season were 31.0%, 20.1% and 37.1% for wheat, and 25.6%, 16.8% and 34.9% for maize, respectively.

Discussion

Imbalanced fertilization by over-application of N and P has presented a great challenge in North Central China in recent years and has resulted in losses of yield and profits for farmers and the environmental effects require addressing more urgently (Zhu, 2002; Zhao et al., 2006). In this study, the improved nutrient management increased yield by saving fertilizer N and P input and increasing nutrient use efficiency. However, compared with developed countries, the nutrient use efficiency in China is still very low. Dobermann et al. (2007) reported that PFP_N, AE_N and RE_N in cereals varied between 40–80 kg kg^{-1}, 10–30 kg kg^{-1} and 30–50%, respectively, and could reach >60 kg kg^{-1}, >25 kg kg^{-1} and 50–80%, respectively, in a well-managed system, with low levels of N use, or with low soil N supply. In the current study, most PFP_N values were lower than 40 kg kg^{-1}, those of AE_N lower than 10 kg kg^{-1} and RE_N values lower than 35% because of continuous high N input in recent years in North Central China (Zhao, 1997; Chen, 2003; Cui, 2005), which was in accordance with the lower N use efficiency due to increases in N use reported by Dobermann et al. (2007) for developing countries. The low nitrogen use efficiency (Table 4) in the current study means that additional in-season N management strategies are needed, such as using a chlorophyll meter or leaf color chart in rice (Dobermann, 2003), but little information is available in the wheat–maize rotation system. Therefore, designing a 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. Although many sensing devices and approaches have been developed for such purposes (Scharf et al., 2006; Varvel et al., 2007), they are not yet widely used in wheat and maize. Specific algorithms for in-season prescription of uniform N based on crop diagnostics have to be evaluated more rigorously. In any case, because crop greenness can only be sensed reliably after about the V6 stage of maize and is also affected by numerous factors other than N, the reactive N management approach tends to correct for differences in crop N status. 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, i.e., 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.

More importantly, because yield potential and nutrient availability is determined by many factors other than nutrients, the best nutrient management strategies must be integrated with other agronomic practices. These practices may include investment in high-yielding cultivars with stress tolerance, algorithms and support services for better fertilizer recommendations, better soil and crop management technologies, extension education, and local regulation of excessive N or P use by both the public and the private sector to increase nutrient use efficiency as in developed countries.

Acknowledgments

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