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Nitrogen use efficiency in a wheat–corn cropping system from 15 years of manure and fertilizer applications

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ABSTRACT

Low nitrogen use efficiency (NUE) and adverse environmental impacts caused by N fertilization increasingly threaten the sustainability of agriculture. To develop strategies for efficient nutrient management, we investigated the effects of long-term (1991–2005) various fertilization regimes on yield, NUE and N agronomic efficiency (NAE) in a wheat–corn cropping system at four sites (Changping, Zhengzhou, Yangling, and Qiyang) in China. Treatments included unfertilized control (CK), chemical fertilization only (N, NP, NK, and NPK), manure application (supplying 70% N) with NPK (NPKm) and at 1.5× rate (1.5NPKm), and NPK with corn stover returned (NPKs). The NP and NPK treatments resulted in generally higher yield, NUE and NAE than the N and NK for both wheat and corn demonstrating the importance of P in NUE improvement. The manure treatments resulted in significant increase or no decrease in the overall system NUE in all four sites with the highest mean NUE (49%) from NPKm treatment. In acid soil at Qiyang, only manure treatments resulted in significant increases of NUE and NAE indicating the importance of organic amendment. Wheat was more responsive to P fertilizer and corn was more responsive to manure in NUE improvement. Thus an effective nutrient management strategy is to ensure adequate P supply for the wheat crop and manure application for the corn crop to improve overall NUE for the wheat–corn production system.

1. Introduction

Wheat (*Triticum aestivum* L.) and corn or maize (*Zea mays* L.) are among the most important food crops, accounting for 27% and 33% of the total cereal production in the world (FAO, 2008). Since the 1960s, there has been an increasing global demand for both wheat and corn due to the world's rapid population growth and economic development. This is particularly true in China where wheat and corn are grown in succession in a single year on about 49.2 million ha of land (47.1% of China's agricultural land) producing 48.9% of total annual crop yields (CAY, 2006). Rotation systems involved with wheat–corn are popularly used in many countries such as United States, Canada and Romania (Barbaricka et al., 2012; Cociu, 2012; Dayegamiye et al., 2012).

High inputs of chemical nitrogen (N) have been used globally to increase crop yields. Approximately 23 million tonnes of N fertilizers were applied in 2008 in China, accounting for about 30% of the total world N consumption (National Bureau of Statistics of China, 2009). However, crop yields have been increasing at a much lower rate than the increase in fertilizer applied (Vitousek et al., 2009). For instance, from 1990 to 2008 application of N fertilizer in China increased by ~50%, but crop yields only increased by ~10% (National Bureau of Statistics of China, 2009). This has resulted in particularly low N use efficiency (NUE). In China, NUE for the wheat–corn rotation is as low as 26–31%, and a large amount of applied N (~180 kg ha^{-1} yr^{-1}) is lost to the environment (Miao et al., 2011). Since the 1990s, this has resulted in serious environmental degradation including eutrophication of surface waters, nitrate pollution of groundwater, acid rain, soil acidification, greenhouse gas emissions, and other forms of air pollution

Abbreviations: NUE, nitrogen use efficiency; NUE, nitrogen agronomic efficiency; CK, control; NPKm, chemical nitrogen, phosphorus, and potassium fertilizer plus manure; 1.5NPKm, 1.5 rate of NPKm; NPKs, chemical NPK with corn stover returned; PC, P fertilizer contribution; KC, K fertilizer contribution; MC, manure contribution.

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(Ju et al., 2009). Improved management practices that maximize crop yield and maintain soil productivity while minimizing environmental impact are urgently needed.

Long-term field experiments are essential tools to assess and develop effective management practices on nutrients for sustainable crop production, soil fertility, and environmental impact (Richter et al., 2007). Rasmussen et al. (1998) concluded that networks of long-term agroecosystem experiments are crucial for making regional projections regarding agricultural sustainability and evaluation of the impacts on global climate change. Long-term experiments are valuable for revealing changes in soil fertility and crop yields that cannot be revealed in short-term studies as illustrated for various cropping systems (wheat–corn cropping, wheat–rice cropping, triple-rice cropping, and wheat or corn single cropping) by Zhao et al. (2010). These studies, however, did not conduct detailed analysis of the NUE, which becomes crucial to assessing the long-term sustainability of cropping systems especially with the increasing awareness of groundwater contamination from nitrate leaching and greenhouse gas emissions.

To develop efficient nutrient management practices for one of the most popular cropping systems with wheat–corn rotations, long-term experiments were established in 1990 to examine the effects of continuous applications of chemical fertilizer and manure on crop yield and NUE in several highly productive regions across China. The effects of fertilization treatments on corn grain yield and NUE based on 15 year data were examined and reported in detail by Duan et al. (2011). The corn data led to conclusions that manure applications resulted in more stable and significantly higher yield, higher NUE, and increased soil nutrient storage with the most significant improvement in an acid soil. Manure and P applications were identified as the most important factors to improve corn yield and NUE. The NUE data evaluated have implications on the overall N used by crops or total N loss from fertilizer application. To evaluate the economic return from fertilizer application, the N agronomy efficiency (NAE) can be examined. The objectives of this paper were to (1) examine the effects of long-term fertilization treatments on the yield, NUE and NAE of wheat in the wheat–corn cropping systems and compare with those for corn; (2) determine the overall NUE of the wheat–corn cropping system; and (3) develop efficient nutrient management strategies for the crop rotation systems. The results can be useful for similar wheat–corn cropping systems in many other regions around the world.

2. Materials and methods

2.1. Site description and cropping practices

Long-term experiments were established in 1990 at four sites covering the major wheat–corn production regions in China. The study sites were at Changping (40°13′12″N, 116°15′23″E), Zhengzhou (34°47′25″N, 113°40′42″E), Yangling (34°17′51″N, 108°00′48″E) and Qiyang (26°45′12″N, 111°52′32″E) from north to south. Detailed information about soil types, chemical properties prior to the experiments, and climate conditions for the study locations can be found in Duan et al. (2011). One study site is located in the north (Changping) and two in the central (Zhengzhou and Yangling) regions of China. These three sites have similar precipitation and temperature (i.e. a warm temperate climate). The 4th site, Qiyang, is in the south and in the region with a subtropical climate. The annual precipitation (1408 mm) and mean annual temperature (18 °C) at Qiyang are much higher than other three sites (525–646 mm and 13–15 °C) resulting in an acid soil due to high leaching. Soil at Qiyang is developed from quaternary red clay and contains higher content of clay (41%) than the other sites (10–17%). With undetectable $CaCO_3$ and low cation exchange capacity (CEC) (10 cmol kg^{-1}), soil pH at Qiyang (5.7) is significantly lower than the other three sites (8.3–8.7). From 1988 to 1989, local wheat and corn cultivars were grown without fertilization to reduce soil fertility variability in all four crop fields. The total N, available P and available K content were 0.6–1.1 g kg^{-1}, 5–11 mg kg^{-1} and 65–122 mg kg^{-1}, respectively, in 1990 before the field experiment establishment at the four sites.

At Changping, Zhengzhou and Yangling, winter wheat is sown in early October and harvested in early June the following year; corn is then planted in June immediately after wheat and harvested in mid-September. At Qiyang, winter wheat was sown in early November and harvested in early May in the following year; corn was sown between the wheat strips in early April and harvested in July. Local wheat cultivars "8693", "Zhengmai 9023", "Shan 253" and "Yedan 13", and corn cultivars "Tangkang 5", "Zhengdan 8", "Gaonnong 1", and "Xiangmai 4" were grown at Changping, Zhengzhou, Yanling, and Qiyang, respectively.

2.2. Experiment design and fertilization management

The four study sites were designed as one full experiment by including the same number of treatment at each site, i.e., the treatments were replicated at the four study sites but not at the individual site, which was limited by the size of available fields and the requirement for large treatment plot allowing typical growers' practice or operation to be applied. Eight treatments included in this study were: (1) unfertilized control (CK); (2) chemical N (N); (3) chemical N and P combination (NP); (4) chemical N and K combination (NK); (5) chemical N, P and K combination (NPK); (6) chemical NPK combinations with manure (NPKm); (7) 1.5× the application rate in Treatment 6 (1.5NPKm); (8) chemical NPK combinations with corn stover returned (NPKs). In all sites the chemical source of N was urea, the source of P was superphosphate and the source of K was K_2SO_4 except that KCl was used at Qiyang. Depending on local availability, the manure source varied with pig manure at Changping and Qiyang, horse and cow manure at Zhengzhou, and cow manure at Yangling. The manure rate applied to each site varied slightly, adjusted by N content to supply 70% of the total N for the treatment. All the corn stover harvested from each NPKs plot was returned to the same plot annually. Due to the limited time between wheat harvest and corn planting, farmers do not normally return the wheat straw to the field. Thus in these experiments, wheat straw was removed from the research plots after harvest.

Fertilizer application rates varied a little among the three sites in the north and central region, but much lower at Qiyang according to the local cultivar, potential yield, climate, and soil conditions. The winter wheat yield was often low at Qiyang due to higher temperatures; thus lower amounts of nutrients were applied during the wheat growing season at Qiyang than at the other three sites. The annual application rates of nutrients for wheat were 150, 165, 165 and 190 kg N ha^{-1}, 32, 36, 58 and 16 kg P ha^{-1}, and 31, 69, 69 and 30 kg K ha^{-1} at Changping, Zhengzhou, Yangling and Qiyang, respectively. Due to the complications in balancing all nutrient applications only total N (not P and K) in the manure source was considered. This resulted in additional input of P and K in the manure treatments compared to the chemical fertilizer treatments. Half of the N fertilizer and all of the P and K fertilizers were applied as preplant fertilizers. The remaining N fertilizer was applied as a top dressing during the growing season. The detailed sources and nutrient content in manure were presented previously (Duan et al., 2011).

All treatments in each site were randomized in the first year and the plot received the same treatment in the following years at all four study sites. The treatment plot size was 200 m^2 (20 m × 10 m), 400 m^2 (25 m × 16 m), 196 m^2 (14 m × 14 m), and 200 m^2 (20 m × 10 m) at Changping, Zhengzhou, Yangling, and Qiyang sites, respectively. To avoid edge effects, the treatment plots were separated by 100-cm deep concrete barriers at all sites.

2.3. Soil and plant sampling and analysis

Soil samples were collected at the beginning (1990) and during the 15 years of long-term experiments. Soil samples were collected every year approximately 15 days after the corn was harvested. To collect a representative sample, a total of 20 soil cores from each plot were collected and mixed to produce five composite subsamples for analysis. Changing rates of total N, available N, P and K content in the soil over time were analyzed and the data were reported in detail in a previous paper (Duan et al., 2011). The results will be discussed or summarized in this paper as needed.

Data on wheat plant samples were collected similarly as for the corn measurement described in Duan et al. (2011). Yield was determined for the whole treatment plot. All the above-ground biomass was harvested, removed from the plots, and measured. Upon harvest, five composited straw and grain samples were sampled in each plot for N analysis. Means of the sample analyses were used in reporting.

2.4. Statistical analysis

Considering that the treatments were replicated at four different sites and the same treatment as applied to the same plot over the years, a mixed model was used to statistically analyze the effects of treatments and time (year), as well as their interactions, on the outputs (e.g., annual yield and NUE). In the mixed model, treatments and time were chosen to be the fixed effects and the site was the random effect. The analysis was conducted using SAS 9.2. (SAS Institute, 2008). Further multiple comparisons of the treatment effects were conducted for data from all four sites and no comparison among treatment effects can be performed in each individual site. A Tukey–Kramer adjustment was used to avoid Type I errors in this study. To examine the time effect, linear regressions and hyperbolic relationships were used to evaluate the changes or trends in grain yield and NUE during the 15 years using SigmaPlot (SigmaPlot 10.0, 2006, Systat Software, Inc.). For NAE, because its changes were similar to that of NUE, we focus on evaluation of this economic return parameter on the specific crops and its comparison with NUE.

2.5. NUE calculation and fertilizer contribution analysis

Nitrogen use efficiency can be described in different ways depending on the objective of analysis (Bandyopadhyay and Sarkar, 2005). The NUE (based on total biomass or crop uptake) and agronomic N efficiency (NAE, based on the yield) are employed in this study. The NUE has implications on total N used or lost in crop production and is used to address environmental pollution issues from N fertilizer use. The economic return (grain yield) from fertilizer application is evaluated with the NAE. The two terms are often closely correlated; however, in some cases, higher biomass may not necessarily lead to a higher yield that will result in differences between NUE and NAE.

The NUE of wheat is defined as the uptake of N by the plant from fertilization divided by the total applied N and was calculated in the same manner as corn (Duan et al., 2011).

$$\mathrm{NUE} = \frac{U_{WN} - U_{W0}}{A_{WN}} \times 100\% \tag{1}$$

where U_{WN} (kg N ha^{-1}) is the total N uptake by wheat (grain and straw) from treatments with N fertilizer application, and U_{W0} (kg N ha^{-1}) is the total N uptake by wheat (grain and straw) from treatments without N fertilization and A_{WN} (kg N ha^{-1}) is the amount of fertilizer applied (N in inorganic fertilizer and total N in manure). The N in roots was not considered in the computations due to practical experimental difficulties and insignificant biomass.

The NAE is defined as the grain yield (for either wheat or corn) from N application over the total N applied (Peng et al., 2006; Chuan et al., 2013).

$$\mathrm{NAE} = \frac{Y_N - Y_0}{A_N} \tag{2}$$

where Y_N (kg grain ha^{-1}) is the grain yield from treatments with N fertilizer, Y_0 (kg grain ha^{-1}) is the grain yield from treatment without N fertilizer and A_N (kg N ha^{-1}) is the amount of fertilizer applied (N in inorganic fertilizer and total N in manure).

The annual overall wheat–corn system NUE was calculated as shown in Eq. (3):

$$\mathrm{NUE} = \frac{U_{WN} + U_{CN} - U_{W0} - U_{C0}}{A_{WN} + A_{CN}} \times 100\% \tag{3}$$

where U_{CN} and U_{C0} (kg N ha^{-1}) are the total N uptake by corn from treatments with N fertilizer application and without N fertilizer application, respectively, and A_{CN} (kg N ha^{-1}) is the amount of N fertilizer applied during corn growing season.

To analyze the cumulative effect of the fertilization regime, we focused on the analysis of NUE by determining the NUE trends or the annual change rate (% yr^{-1}) using the least squares linear regression (Tang et al., 2008).

$$Y = a + bX \tag{4}$$

where Y is the NUE (%), a is the intercept (i.e. the initial NUE), b is the slope (changes in NUE per year), and X is the time (year).

The contributions of fertilizer sources as P (PC), K (KC), and manure (MC) to the increase of wheat and corn yield and NUE were estimated. The PC to crop yield or NUE increase was calculated as the yield or NUE difference between NPK and NK treatments divided by the yield or NUE from the NK treatment by referring to the method applied by Tang et al. (2008).

$$\mathrm{PC} = \frac{Y_{NPK} - Y_{NK}}{Y_{NK}} \times 100\% \tag{5}$$

where Y_{NPK} and Y_{NK} (kg grain ha^{-1}) are the grain yield or NUE from NPK and NK treatments, respectively. Using the similar approach, the KC to crop yield or NUE increase was calculated based on the difference between NPK and NP treatments.

$$KC = \frac{Y_{NPK} - Y_{NP}}{Y_{NP}} \times 100\% \tag{6}$$

where Y_{NP} (kg grain ha^{-1}) is the grain yield or NUE from NP treatments.

The MC to crop yield or NUE increase was calculated as the yield or NUE difference between the NPKm and NPK treatments divided by the yield or NUE from the NPK treatment.

$$\mathrm{MC} = \frac{Y_{NPKm} - Y_{NPK}}{Y_{NPK}} \times 100\% \tag{7}$$

where Y_{NPKm} (kg grain ha^{-1}) is the grain yield or NUE from the NPKm treatments.

Table 1
Tests of fixed effects on wheat yield in long-term (1991–2005) fertilization experiment.

Effect	Numerator d.f.	Denominator d.f.	*F* value	*P* > *F*
Year	14	303	3.85	<0.0001
Treatment	7	23.5	18.6	<0.0001
Year × treatment	98	284	0.86	0.8082

Table 2
Average annual wheat and corn grain yield or above ground biomass (Mg ha^{-1}) under various long-term (1991–2005) fertilization treatments at four study sites.

Sites	Treatments							
	CK	N	NP	NK	NPK	NPKm	1.5NPKm	NPKs
Grain yield of wheat (Mg ha^{-1})								
Changping	0.6 (0.1) [a]	0.7 (0.1)	2.9 (0.2)	0.9 (0.1)	3.5 (0.3)	4.0 (0.3)	3.9 (0.3)	3.5 (0.2)
Zhengzhou	1.9 (0.1)	2.2 (0.2)	6.3 (0.3)	2.7 (0.3)	6.4 (0.2)	5.9 (0.2)	6.4 (0.2)	6.2 (0.2)
Yangling	1.0 (0.1)	1.0 (0.1)	5.2 (0.3)	1.2 (0.3)	5.4 (0.3)	5.6 (0.4)	5.8 (0.3)	5.5 (0.3)
Qiyang	0.4 (0.03)	0.4 (0.1)	1.0 (0.1)	0.5 (0.1)	1.2 (0.1)	1.6 (0.1)	1.7 (0.1)	1.3 (0.1)
Mean	1.0 [b]	1.1 b	3.9 a	1.3 b	4.1 a	4.3 a	4.4 a	4.1 a
Straw weight of wheat (Mg ha^{-1})								
Changping	1.0 (0.1)	1.4 (0.2)	4.6 (0.5)	1.6 (0.3)	4.8 (0.3)	5.8 (0.4)	6.0 (0.5)	4.9 (0.4)
Zhengzhou	2.2 (0.2)	2.4 (0.2)	6.6 (0.4)	2.8 (0.3)	7.2 (0.5)	8.0 (1.1)	7.9 (0.6)	7.6 (0.6)
Yangling	1.8 (0.1)	2.2 (0.3)	6.4 (0.4)	2.1 (0.2)	7.2 (0.5)	8.7 (0.7)	9.0 (0.5)	7.6 (0.5)
Qiyang	0.9 (0.1)	1.2 (0.3)	2.1 (0.4)	1.2 (0.3)	2.3 (0.4)	3.6 (0.3)	4.2 (0.4)	2.8 (0.5)
Mean	1.5 b	1.8 b	4.9 a	1.9 b	5.4 a	6.5 a	6.8 a	5.7 a
Grain yield of corn (Mg ha^{-1})								
Changping	1.9 (0.2)	2.3 (0.3)	4.2 (0.4)	2.5 (0.3)	4.8 (0.4)	5.4 (0.4)	5.1 (0.4)	4.9 (0.3)
Zhengzhou	3.2 (0.2)	3.8 (0.4)	6.2 (0.3)	4.5 (0.4)	6.3 (0.4)	6.6 (0.4)	6.8 (0.4)	7.0 (0.4)
Yangling	2.2 (0.1)	3.0 (0.2)	6.3 (0.2)	3.5 (0.4)	6.1 (0.3)	6.6 (0.3)	6.9 (0.4)	6.6 (0.3)
Qiyang	0.6 (0.1)	2.1 (0.3)	3.3 (0.3)	2.4 (0.3)	3.6 (0.3)	5.1 (0.3)	6.2 (0.3)	4.1 (0.4)
Mean	1.8 c	2.4 c	4.7 ab	2.9 bc	5.2 a	6.0 a	6.3 a	5.6 a
Stover weight of corn (Mg ha^{-1})								
Changping	3.3 (0.4)	3.6 (0.4)	4.8 (0.7)	5.4 (0.6)	5.8 (0.6)	6.1 (0.5)	6.0 (0.7)	5.4 (0.6)
Zhengzhou	3.2 (0.3)	3.0 (0.3)	4.8 (0.3)	5.6 (0.3)	5.6 (0.4)	6.1 (0.4)	5.9 (0.5)	5.6 (0.4)
Yangling	2.0 (0.1)	2.4 (0.2)	3.3 (0.1)	3.8 (0.1)	4.3 (0.1)	4.1 (0.2)	3.5 (0.2)	3.8 (0.2)
Qiyang	0.9 (0.1)	1.1 (0.3)	2.1 (0.3)	2.7 (0.3)	4.8 (0.3)	5.9 (0.3)	3.5 (0.3)	2.7 (0.4)
Mean	2.4 d	2.5 cd	3.8 abcd	3.0 bcd	4.4 abc	5.1 a	5.5 a	4.7 ab

[a] Values in parentheses are standard deviations of the mean that was averaged for 15 year long-term experimental period.
[b] Different letters in the same row indicate significant differences between treatments at $P < 0.05$ according to Tukey–Kramer adjustment.

3. Results

3.1. Response of wheat yield to fertilization treatments

Statistical analysis on yield data collected from all four study sites showed that the treatment and year both had a significant effect on the wheat grain yield, but their interaction was not significant (Table 1). In most cases, significantly higher yields were obtained from the NP, NPK, NPKm, 1.5NPKm and NPKs treatments compared to the CK, N and NK treatments (Table 2). There were no significant differences in grain yield between the treatments of N and NK, NP and NPK, NPK and NPKs, and NPKm and 1.5NPKm, indicating that K application, stover return, and higher amounts of manure, did not significantly increase yield.

Based on the average yield across the 15 years, manure application in the NPKm treatment resulted in an average 33% grain yield increase at Qiyang compared to the NPK treatment, while little differences were observed at the other three sites (Table 2). However, the NPKm treatment increased the wheat straw weight by 21%, 11%, 21% and 57% at Changping, Zhengzhou, Yangling and Qiyang, respectively, compared to the NPK treatment. The total biomass of wheat (grain plus straw) was increased by 18%, 2%, 13% and 51% at Changping, Zhengzhou, Yangling and Qiyang, respectively, by the NPKm treatment compared to the NPK treatment.

Linear regression analyses showed declining yield (−0.03 to −0.15 Mg ha^{-1} yr^{-1}) for the N and NK treatments ($\alpha = 0.01$) during the 15 year study (Fig. 1 and Table 3). The balanced nutrient treatments (NPK, NPKm, 1.5NPKm and NPKs) resulted in unchanged yields of wheat at Changping and Zhengzhou, and increased yields over time at Yangling ($\alpha = 0.05$ or 0.01). At Qiyang, the wheat yield declined significantly for all the chemical treatments and the NPKs treatment at rates ranging from −0.01 to −0.10 Mg ha^{-1} yr^{-1} and had no significant decrease only for the NPKm and 1.5NPKm treatments over the 15 years.

3.2. Nitrogen use efficiency of wheat

Fig. 2 shows the annual wheat NUEs over the period of 1991–2005 in response to fertilizer treatments at the different study sties. The NUE of wheat was clearly in an increasing trend and higher in the NP and NPK treatments than in N and NK treatments. While decreasing in the N and NK treatments, the NUE of wheat in the NP treatment showed increase at Yangling while unchanged at Changping and Zhengzhou, and declined at Qiyang (Table 4). The NUE of wheat increased at rates of 1.8–4.1% yr^{-1} at Changping and Yangling, and did not change over time at Zhengzhou in the balanced nutrient treatments (NPK, NPKm, 1.5NPKm and NPKs). At Qiyang, the NUEs of wheat declined significantly ($\alpha = 0.01$) for all

Table 3
Increased rate (Mg ha^{-1} yr^{-1}) of grain yield of wheat over the period of 1991–2005 from various fertilization treatments at the four study sites.

Sites	Treatments							
	CK	N	NP	NK	NPK	NPKm	1.5NPKm	NPKs
Changping	−0.05**	−0.06**	−0.02	−0.10**	0.11	0.12	0.12	0.07
Zhengzhou	−0.03	−0.12**	0.06	−0.15**	−0.03	0.08	0.07	0.05
Yangling	−0.03	−0.07**	0.09	−0.03**	0.12*	0.16**	0.12*	0.14**
Qiyang	−0.01*	−0.09**	−0.10**	−0.10**	−0.09**	−0.01	−0.02	−0.09**

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.

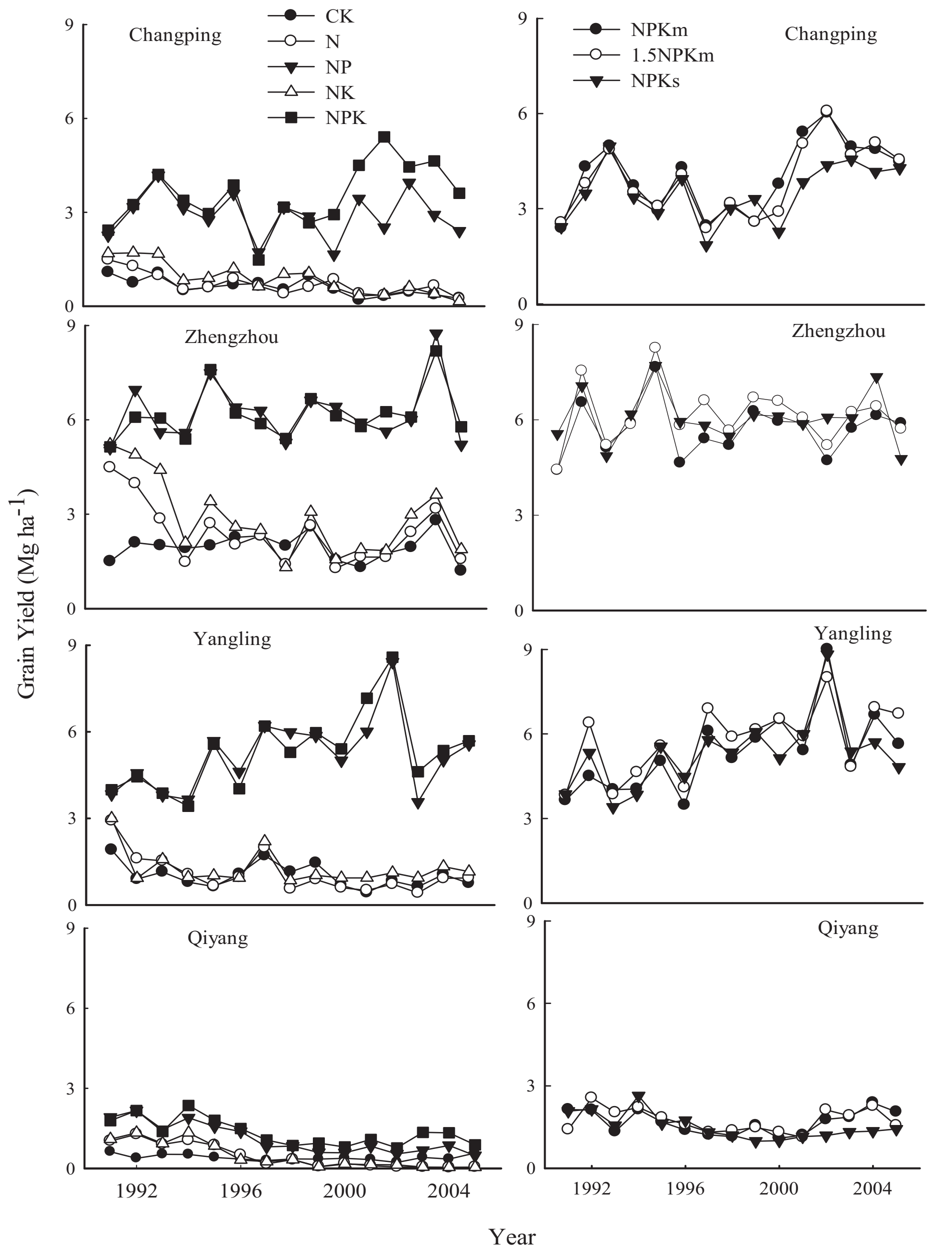

Fig. 1. Changes of annual wheat grain yield from 1991 to 2005 from chemical (left graphs) and mixed chemical and organic (right graphs) fertilization treatments at the four study sites.

Table 4
Changing rate of nitrogen use efficiency (NUE) in wheat and corn over the period of 1991–2005 from various fertilization treatments at the four study sites.

Sites	Treatments						
	N	NP	NK	NPK	NPKm	1.5NPKm	NPKs
Wheat NUE (% yr^{-1})							
Changping	–0.6**	0.5	–1.5**	2.9**	2.8**	2.6**	2.2**
Zhengzhou	–1.4**	0.3	–1.9**	0.6	0.2	0.2	–1.4
Yangling	–1.7**	2.1**	–0.1*	2.7**	4.1**	2.4**	1.8**
Qiyang	–3.3**	–4.3**	–4.0**	–3.0**	–0.1	–0.1	–3.2**
Corn NUE (% yr^{-1})							
Changping	0.3	2.3**	0.2	2.7**	2.5**	2.9**	2.8**
Zhengzhou	–1.4**	0.2	–0.8**	1.3	1.1	0.4	0.4
Yangling	–1.9**	0.8	–0.6**	1.6**	1.3	1.1	0.2
Qiyang	–2.6**	–2.7**	–2.4**	–1.6**	1.9**	1.4**	–1.0

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.

the chemical treatments including the NPK and NPKs treatment at rates ranging from 3% yr^{-1} to 4% yr^{-1}, and no significant changes were observed for the NPKm and 1.5NPKm treatments over the 15 years. However, towards the end of the study period, the manure treatments showed consistent increase or higher NUEs than others and also higher NUEs from NPKm than that from the 1.5NPKm treatment (Fig. 2).

Compared with the NPK treatment, the NPKm fertilization treatment increased the average NUE only at Qiyang by 15% and a steady NUE increase was observed during the last 7 years of the experiment (Fig. 2) although no significant increase rate was concluded during the 15-yr study period (Table 4). The average NUE over 15 years for the NPK and NP treatments (59% and 53%, respectively) was 4–5 times higher than for the NK and N treatments (14% and 11%, respectively). This indicates the importance of P application in enhancing wheat NUE.

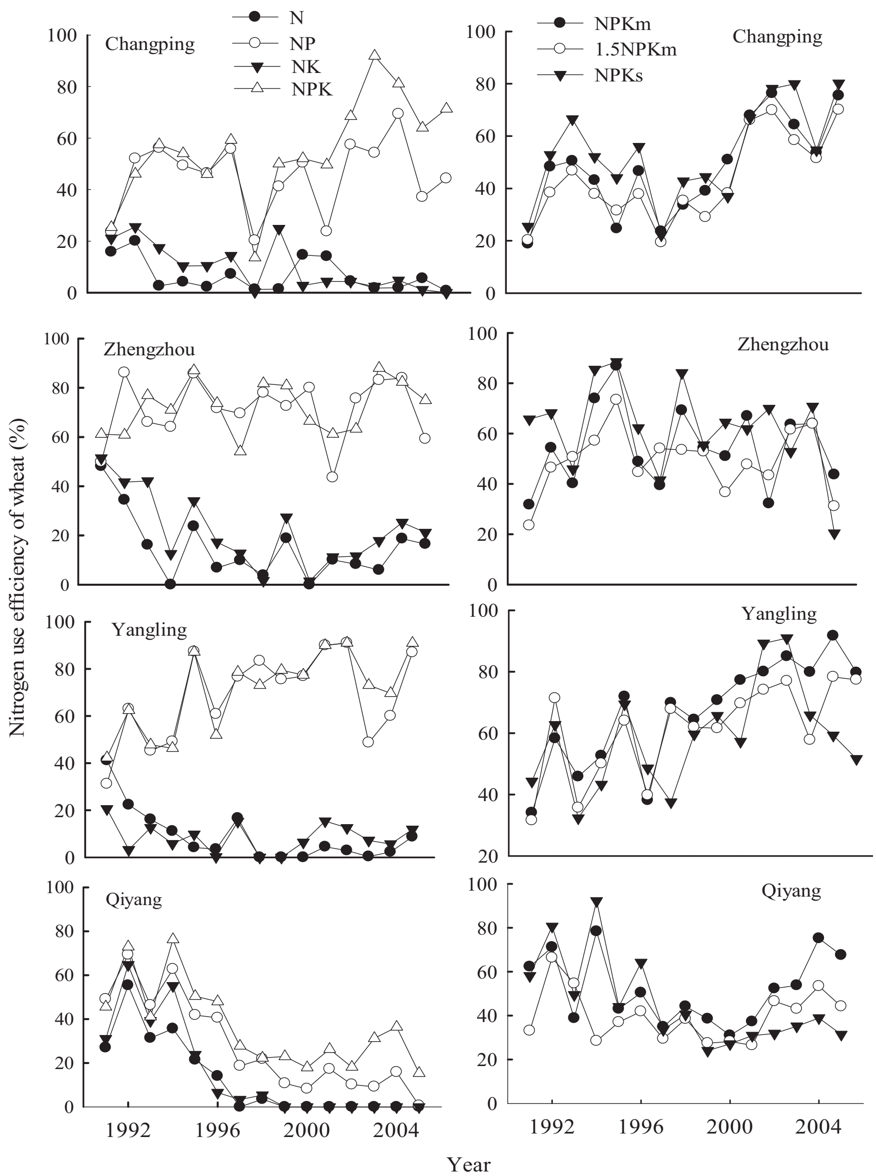

Fig. 2. Changes of nitrogen use efficiency of wheat from 1991 to 2005 from chemical (left graphs) and mixed chemical and organic (right graphs) fertilization treatments at four study sites.

3.3. *Nitrogen agronomic efficiency of wheat and corn*

The average annual NAE of four sites for both wheat and corn are given in Table 5. For both crops, the NAE values were significantly higher in the NP, NPK, NPKm, 1.5NPKm and NPKs treatments (7–38 kg kg^{-1}) than in N and NK treatments (1–5 kg kg^{-1}). The NAE in the NPKm treatment was significantly higher than that in the NP treatment for corn while no significant increase was observed for wheat. The highest NAE (29 kg kg^{-1} for wheat and 38 kg kg^{-1} for corn, respectively) was detected in the 1.5NPKm treatment with extremely close values (28 kg kg^{-1} for wheat and 37 kg kg^{-1} for corn, respectively) for the NPKm treatment. While similar NAE ranges were observed between wheat and corn for the chemical fertilizer treatments, the manure and stover returned treatments resulted in higher NAE for corn compared to wheat. The overall NAE (data not shown) for the production system was also examined and showed a similar trend with the NUE. Thus further data analysis is on NUE only.

Table 5
Average nitrogen agronomic efficiency (NAE)[a] (kg kg^{-1}) of wheat and corn over the period of 1991–2005 for various fertilization treatments at the four study sites.

Sites	Treatments						
	N	NP	NK	NPK	NPKm	1.5NPKm	NPKs
Wheat							
Changping	1	15	2	19	23	15	19
Zhengzhou	2	27	5	27	24	18	26
Yangling	0	25	1	27	28	29	27
Qiyang	0	7	1	9	13	14	10
Mean[b]	1 b	19 a	2 b	21 a	22 a	19 a	21 a
Corn							
Changping	3	22	4	25	32	22	26
Zhengzhou	1	23	3	27	31	20	29
Yangling	2	24	2	29	37	38	31
Qiyang	1	7	1	7	13	16	9
Mean	2 d	19 bc	3 d	22 ab	28 a	24 ab	24 ab

[a] The NUE of wheat–corn system was determined using Eq. (3).
[b] Different letters in the same row indicate significant differences between treatments at $P < 0.05$ according to Tukey–Kramer adjustment.

Table 6
Average nitrogen use efficiency (NUE) and the increased rate of NUE for the total wheat–corn system over the period of 1991–2005 for various fertilization treatments at the four study sites.

Sites	Nitrogen use efficiency (NUE) (%)						
	N	NP	NK	NPK	NPKm	1.5NPKm	NPKs
Annual of wheat–corn system [a]							
Changping	10	40	15	49	42	38	48
Zhengzhou	13	53	21	55	48	41	43
Yangling	11	53	14	59	63	48	51
Qiyang	9	22	12	31	45	42	37
Mean[b]	11 b	42 a	16 b	48 a	49 a	42 a	45 a
Increased rate of NUE ($\%\,yr^{-1}$)[c]							
Changping	−0.4	0.9	−1.0	2.8**	2.6**	2.7**	2.3*
Zhengzhou	−1.4*	0.3	−1.3*	1.2	0.9	0.3	−0.1
Yangling	−1.8**	1.9*	−0.4	2.4**	2.7**	1.8*	1.3*
Qiyang	−2.7**	−2.8**	−2.8**	−1.6**	1.2**	0.9*	−1.9*

[a] The NUE of wheat–corn system was determined using Eq. (3).
[b] Different letters in the same row indicate significant differences between treatments at $P < 0.05$ according to Tukey–Kramer adjustment.
[c] The increased rate was determined using a least squares linear regression: $Y = a + bX$, where Y is the NUE of wheat–corn system (%); X is the year; b is the slope (i.e. the NUE change rate).
* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.

3.4. Nitrogen use efficiency of wheat–corn system

To compare the effect of different fertilization regimes on the performance of the two-crop production cycles, the average overall NUE of the wheat–corn system was analyzed and the results are given in Table 6. Averaged over the four sites, significantly higher NUE of the wheat–corn system were obtained for the NP, NPK, NPKm, 1.5NPKm and NPKs treatments compared to the N and NK treatments. No significant differences in the NUE can be determined between or among the treatments in the two groups based on variations among the 4 sites although the NUEs appear very different at different sites. Compared with the N treatment, the overall NUE was increased 30%, 40%, 42% and 13% in the NP treatment, but only increased 5%, 8%, 3% and 3% in the NK treatment at Changping, Zhengzhou, Yangling and Qiyang, respectively. Manure application (NPKm) and stover returned with NPK (NPKs) resulted in net 14% and 6% increases in NUE respectively, from the NPK treatment at Qiyang. The NPKm treatment resulted in little change in the NUE values of the wheat–corn system when compared to the NPK treatment at Changping, Zhengzhou and Yangling. The 1.5NPKm showed relatively lower NUE than the NPKm in all sites possibly due to excess N applied in the treatment.

The annual NUE change rates ($\%\,yr^{-1}$) of the total wheat–corn system were calculated, analyzed using linear regression based on data shown in Fig. 2, and shown in Table 6. At Changping and Yangling, significant increases of NUE were observed for all balanced fertilizer treatments (NPK, NPKm, 1.5NPKm and NPKs). The N and NK treatments resulted in significant decreases of NUE, but for the other treatments there were no changes at Zhengzhou. At Qiyang, all the chemical N, NP, NK and NPK treatments as well as the NPKs resulted in significant NUE decreases and the manure applications (NPKm and 1.5 NPKm) resulted in significant NUE increases. The stover returned (NPKs) treatment showed variations among the four sites, but with a similar effect as the NPK treatment on NUE.

3.5. Contribution of P, K, and manure to wheat and corn yield and NUE increase

Averaged across the four sites, the contributions of P (i.e. PC) to grain yield and NUE increase of wheat were 229% and 398%, respectively, or 2.3–3.4 times greater than that for corn (98% and 118%) (Table 7). The contributions of K (i.e. KC) to grain yield and NUE increase were 1.3–31% for wheat and −3.2% to 44% for corn. The further contributions of manure (i.e. MC) to grain yield and NUE increase of corn were 17% and 14%, respectively, and for wheat were lower (11% and 0.6%). On the whole, PCs were as high as 55–742% based on the improvement of yield and NUE while KCs were relatively insignificant as compared to the PCs. Further contribution of manure to yield and NUE improvement were confirmed for both crops. Between the two crops, wheat was more responsive to P and corn was more responsive to manure applications for both grain and NUE by the higher PC values for wheat than that for corn and higher MC values for corn than that for wheat.

4. Discussion

4.1. Difference in response to fertilization treatment between wheat and corn

The results from this research have shown that manure and P are the most important fertilization treatments to improve the yield and NUE for both wheat and corn (detailed data for corn are reported in Duan et al., 2011). There are significant differences in the crop response to the fertilization treatments. Prior to examination of these differences, it should be noted that the computation of PC was based on NK treatment (low yield and low NUE) and NPK treatment (Eq. (5)); and the MC was based on NPK treatment (higher yield and higher NUE than NK) and NPKM treatment (Eq. (7)). The NPK treatment had substantially higher yield than the NK treatment that resulted in much higher PC values than the MC values; but these values do not necessarily indicate more importance of P than manure. Positive MC values indicate further improvement upon sufficient or high P supply. The crop response to P and manure treatments is discussed below based on the relative differences between the two crops.

The P fertilizer effect on wheat yield and NUE improvement was larger than that observed for corn (Table 7). The contributions of P fertilizer to both grain yield and NUE were higher for wheat, about 2.3–3.4 times that for corn, average of the four sites. Manure, however, did not further improve the yield and NUE of wheat in alkaline soils at Changping, Zhengzhou and Yangling (ave. MC −13% to NUE and 3.4% to yield) but showed significant improvement in the acid soil at Qiyang (33–41%). For corn, manure application increased NUE not only at Qiyang, but also at most other study sites (ave. MC 17% to yield and 14% to NUE) with most MC values relatively higher than that for wheat, though it was not significant in statistical because of the large variability among four sites.

In a similar rotation system, results from a 36-year experiment also showed that wheat was the crop most sensitive and corn was moderate to the absence of P fertilization (Colomb et al., 2007). There were three possible reasons for the different response of wheat and corn to P fertilizer and manure. (1) During the early growth stages of wheat, the mineralization of organic materials and release of P in soil was slow because of low soil temperature (i.e. from early October to early June). This would reduce P availability in soil and limit P uptake by wheat (Sharpley and Ahuja, 1982; Sánchez and Boll, 2005). In contrast, the temperature during the early growth season for corn (i.e. from early June to mid-September) was high, which could lead to greater availability of P in soil, thus increasing the supply of P for corn. (2) The manure applied before the wheat season most likely released P slowly for the wheat growing season, and for the same reason released or increased P supply during its warmer corn growing season from mineralization. (3) The sensitive stage to P nutrient deficiency is the seedling stage for wheat (Romer and Schilling, 1986), but the later period for corn (Girma et al., 2007). The sufficient chemical

Table 7
Contribution of P (PC), K (KC), and manure (MC) (%) to improvement of the mean annual yield and N use efficiency (NUE) at the four study sites.

Sites	PC[a] on grain yield	KC on grain yield	MC on grain yield	PC on NUE	KC on NUE	MC on NUE
Wheat						
Changping	289	21	14	479	23	−14
Zhengzhou	137	1.6	−7.8	230	1.3	−24
Yangling	350	3.8	3.7	742	3.4	−0.4
Qiyang	140	20	33	141	31	41
Mean	229	12	11	398	15	0.6
Corn						
Changping	90	14	13	96	23	−11
Zhengzhou	55	1.6	4.8	86	12	6.8
Yangling	79	−3.2	8.2	139	25	18
Qiyang	166	9.1	42	150	44	44
Mean	98	5.5	17	118	26	14
P-value[b]	0.07	0.37	0.62	0.08	0.29	0.48

[a] Percent changes for PC, KC, and MC were calculated using Eqs. (5)–(7), respectively.
[b] The *P*-value represents the probability to be same between wheat and corn in a same parameter.

fertilizer in earlier stage and slow mineralization of manure led to the different response of wheat and corn to chemical P and manure.

4.2. Nitrogen agronomic efficiency of wheat and corn

High NAE was achieved from the 15 year long field experiment from NPK applied treatments especially with manure applications (Table 5). For corn, the NAE achieved 37–38 kg kg^{-1} in the NPKm or 1.5NPKm treatments. Vanlauwe et al. (2011) was reported that based on over 700 data points, the NAE of corn were in the range of 10–30 kg kg^{-1} and values over 25 kg kg^{-1} were obtained in well-managed systems. The low NAE from all treatments were due to the low grain yield at Qiyang (Table 2). Compared with the NPK treatment, the NPKm treatment increased the NAE of corn by 15–86% at the four study sites. Vanlauwe et al. (2011) also showed that NAE of corn increased from 25 kg kg^{-1} to 38 kg kg^{-1} after manure applied to chemical fertilizer. The very low NAEs (0–5 kg kg^{-1}) for the N and NK treatments indicate that the N and NK treatments resulted in a low increased yield than the control. This was true when unbalanced fertilizer application caused soil physical, biological, or chemical degradation, referred to as “poor, less-responsive soils” by Vanlauwe et al. (2011). Negative NAE value was even detected in Peng et al. (2006) because of the excessive N application.

The NAE values of wheat were in the range of 9–29 kg kg^{-1} for the NPK treatment in our study, which was similar to the values reported in Yadvinder-Singh et al. (2009) for wheat (14–24 kg kg^{-1}). The similar NAE of wheat between NPK and NPKm treatments suggested the manure did not improve NAE, average of the four sites, but much higher NAE in NPKm treatment was found for corn although the difference not significant (Table 5). Aulakh et al. (2000) also showed that the NAE of wheat did not change after manure applied to chemical fertilization and might increase after the ratio of chemical N fertilizer was decreased in the combined fertilization.

The NAE and NUE showed a similar response to fertilization treatments indicating that the grain yield was highly correlated to the biomass production for a crop. However, between crops, the NAE was not completely consistent with NUE because of the different harvest index (HI, ratio of grain/total biomass). The corn had a relatively higher HI (0.43–0.55) than wheat (0.38–0.44) that can be deduced from data in Table 1. The NAE of corn (maximum 38 kg kg^{-1}) was similar to or higher than wheat (maximum 29 kg kg^{-1}), while the NUE of corn (maximum 71%) was always lower than wheat (maximum 91%) at the same sites (Fig. 2; Duan et al., 2011). The data suggested that the corn was more efficient than wheat in converting the N into grain.

4.3. Relationship between soil nutrient status change and NUE

Soil nutrient status changes from the long-term experiment were reported in detail earlier (Duan et al., 2011). In summary, the total N in soil increased significantly under manure application (NPKm and 1.5NPKm) at Changping, Zhenzhou and Yangling and available N increased significantly at Zhengzhou only. The soil available P content increased to some extent in the NP and NPK treatments, and increased substantially in manure treatments. Significant increases in soil available K content were only observed from K fertilizer treatments at Zhengzhou and Yangling.

The relationship between NUE of wheat and soil total N, available P and available K was evaluated using the Mitscherlich equation from Colomb et al. (2007). The results (data not shown) were similar to corn that was discussed by Duan et al. (2011). Total N and available K did not significantly affect the NUE of wheat except for a weak relationship between the available K content and the NUE at Qiyang ($R^2 = 0.2^*$). Available P content in soil, however, had a significant effect on NUE of wheat ($R^2 = 0.3–0.6^*$) at all four sites. The maximum NUEs of wheat predicted by the Mitscherlich equation were 59%, 61%, 69% and 39% at Changping, Zhengzhou, Yangling and Qiyang, respectively. These values suggest that wheat NUE could be increased up to 40–70% by providing sufficient soil P. At the four study sites, the available P content in soil increased in balanced fertilization from the 5–11 mg kg^{-1} in 1990 to 16–27 mg kg^{-1} (NPK treatment) in 2005 from P fertilization.

The NUE of wheat–corn system was significantly improved by manure application at Qiyang and the additional P from manure must have contributed to the improvement. The total P content in Qiyang soil was lower (0.5 g kg^{-1}) than the other three sites (0.6–0.7 g kg^{-1}) in 1990 (beginning of the field experiment) and increased quickly after P fertilizer and manure applications (Duan et al., 2011). Other studies also showed that with P fertilizer application, soil P concentration increases are greater for sites having lower initial soil test *P* values (Dodd and Mallarino, 2005; Anthony et al., 2012).

4.4. Yield and NUE affected by soil and climate conditions

Crop yield and NUE response to fertilization treatments were most likely affected by soil and climate conditions in wheat–corn cropping system based on the observations at the four study sites. Among the three sites in north and central China (Changping, Zhengzhou and Yangling), the improvement of NUE due to K fertilizer was only observed at the Changping site because the available K in 1990 at this site was the lowest (65 mg kg^{-1}) and did not increase to a higher level in soil during the 15 years (Duan et al., 2011). The average NUE of the wheat–corn system was 40% and remained constant during the 15 years for the NP treatment, while increasing to 49% at annual rates of 2.8% yr^{-1} for the NPK treatment at Changping (Table 6). Therefore, K fertilizer should be applied at the northern region where soil K level is low to improve the overall NUE for the wheat–corn production system.

Qiyang is located in southern China and the soil pH was 5.7 in 1990. A significant decline in pH occurred in this type of soil due to chemical fertilization and the annual pH decline ranged from 0.07 to 0.12 pH units (Zhang et al., 2008). This is due to the high precipitation, low cation exchange capacity of the soil, and especially intensified nitrification from inorganic N fertilizer application causing soil acidification. In acids soils, even balanced NPK applications resulted in NUE that decreased over time (Fig. 2) and higher NUE can be achieved only through manure applications. Manure application was found to prevent acid soil from further acidification, which is another important reason for the improvement of NUE by increasing yield and plant N uptake. Therefore, manure applications appear necessary to increase the overall wheat–corn yield and NUE to a greater extent for acid soils compared to alkaline soils due to the benefits of improving acidic soil properties.

4.5. Nutrient management strategies for wheat–corn cropping system

In this study, the average NUE of wheat achieved 38–63% in manure treatments at all four sites. In the acid soil at Qiyang, the manure treatments increased NUE to as high as 70% for wheat. The NUE of corn achieved 54–70% from manure and P fertilizer applications at the four study sites (Duan et al., 2011). The current NUE for wheat and corn in China is about 26–28% (Miao et al., 2011). The reported low NUEs are likely due to either imbalanced nutrient supply or excessive N supply. This long-term field study showed that much higher NUEs can be achieved with balanced nutrient and manure applications or stover returns. The results also illustrate positive gains from the use of more organic sources of nutrients, such as manure, while providing good economic benefits to the farmers.

As the wheat yield showed more improvement in response to P fertilizer than corn and corn yield showed more improvement to manure applications, it is therefore recommended to emphasize the P supply for wheat and manure application for corn to improve NUE further in the rotation system in China. It should be noted, however, that P fertilizer has been over used in some parts of China and there were excess amounts of P in soil. In this case, caution must be taken and no P fertilization should be recommended to avoid losses of P to the environment. Determination of soil P level is necessary for effective nutrient management.

The overall NUE of wheat–corn system can be increased to 63% (Table 6) by the application of P fertilizer and manure with proper amount and timing. However, nutrient dynamics from fertilizer, especially manure, and its relationship to plant requirements are not well understood. For a better understanding of the different response of crops to fertilization, the physiological process of nutrient in crops and after effect of fertilization should be examined further. Nutrient release from manure application needs to be characterized so that this knowledge can assist in decision making on application timing for efficient plant uptake. Precision nutrient management systems need to be established that respond to not only the field-to-field and year-to-year variability in nutrient supply and crop demand for a single crop, but also for the integrated production systems. The information gained from this long-term research is valuable for further research and will help to develop effective nutrient management strategies that will lead to more balanced nutrient approach, less reliance on chemical fertilizers, increased nutrient-use efficiencies, reduced environmental degradation, and ultimately sustainable intensification.

5. Conclusions

Based on the 15-year long field research, crop yield and nitrogen use efficiencies can be significantly improved for the wheat–corn cropping system by management strategies for both chemical and manure fertilizer sources. The NUE of overall rotation system was 40–60% in well balanced fertilization treatments. The balanced fertilization especially with manure applications resulted in high grain yield, increased NUE at three alkaline soils. The NUE improvement from manure applications was more significant in acid soil than in alkaline soils. Phosphorus was clearly one of the key factors to improve NUE of the system in all study sites. Phosphorus fertilizer was more effective to improve yield and NUE for wheat than for corn, while manure application effect was relatively greater for corn than for wheat. Although similar NAE was obtained for both wheat and corn, the higher biomass of corn leads to high NUE values than for wheat. These results can guide chemical fertilizer and manure application to improve the system production and NUE. There is a great need for further understanding the dynamics of N from manure application to increase its nutrient use efficiency and minimize potential impact on soil productivity.

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