



## Establishing a scientific basis for fertilizer recommendations for wheat in China: Yield response and agronomic efficiency

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### ABSTRACT

The inappropriate application of fertilizer has become a common phenomenon in wheat production systems in China and has led to nutrient imbalances, inefficient use and large losses to the environment. However, defining an appropriate fertilization rate remains the foundation to science-based nutrient management. This paper described a new fertilizer recommendation method for wheat in China based on yield response and agronomic efficiency using datasets from 2000 to 2011. The results showed that the mean yield responses of wheat to N, P and K were 1.7, 1.0 and 0.8 t/ha, respectively. Nitrogen was the nutrient most limiting yield, followed by P and then K. The soil indigenous nutrient supplies were 122.6 kg N/ha, 38.0 kg P/ha, and 120.2 kg K/ha. The mean agronomic efficiencies were 9.4, 10.2 and 6.5 kg/kg for N, P and K, respectively. There was a significant negative exponential relationship between yield response and indigenous nutrient supply, and a significant negative linear correlation between yield response and relative yield. It was also demonstrated a quadratic equation between yield response ( $x$ ) and agronomic efficiency ( $y$ ) ( $P < 0.05$ ). The relationship between yield response ( $x$ ) and agronomic efficiency ( $y$ ) for N was  $y_N = 0.3729x_N^2 + 6.1333x_N + 0.1438$  ( $R^2 = 0.76$ ,  $n = 601$ ), for P was  $y_P = 0.5013x_P^2 + 8.3209x_P + 2.3907$  ( $R^2 = 0.65$ ,  $n = 288$ ), and for K was  $y_K = 1.6581x_K^2 + 9.099x_K + 0.7668$  ( $R^2 = 0.58$ ,  $n = 379$ ). These equations were all incorporated as part of the *Nutrient Expert for Wheat* fertilizer recommendation decision support system. The results of multiple field experiments helped to validate the feasibility of the recommendation model and concluded that *Nutrient Expert for Wheat* could be used as an alternative method to make fertilizer recommendations in China.

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### 1. Introduction

Wheat (*Triticum aestivum* L.) is one of the important cereal crops in China, and fertilizer applications have played a major role in increasing yield. However, in the pursuit of meeting food security in China, over-application of N fertilizer has been a common practice in wheat production systems and has led to nutrient imbalances, inefficient fertilizer use and large losses to the environment (Cui et al., 2008a; Ju et al., 2009). Having access to a science-based fertilizer recommendation is critical for improvement of fertilizer use efficiency in high yielding crops. However, how to establish

fertilizer recommendations suitable for smallholder farming households in China remains a challenge.

Soil testing method has been developed as a means of improving fertilizer use efficiency in China. He et al. (2009) did multiple-point field experiments based on soil testing in North Central China and showed that soil test based fertilizer recommendations could increase wheat and maize yield and improve fertilizer use efficiency. However, there are challenges associated with soil testing, including taking representative soil samples, identifying an analytical method suitable for the location soils, and establishing a method which predicts soil nutrient supply capacity. Additionally, soil testing is time-consuming and expensive. In smallholder farming households, the main management units in China, soil testing is viewed as a very expensive tool, and the time required to get results are often not feasible in multiple cropping situations. Even if soil test values are suitable, there still remains the challenge of selecting a science-based fertilizer recommendation philosophy (Hou et al., 2002; He et al., 2012).

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Nutrients for plant uptake come from both external inputs such as fertilizer and manure, but also the soil itself. In  $^{15}\text{N}$ -labeled micro-plot experiments of wheat, Ju et al. (2002) showed that there was 45% of the total nitrogen uptake coming from the fertilizer, and 55% from the soil. Soil nutrient mineralization is often used as a means of assessing soil indigenous nutrient supply in an unfertilized crop. Results showed that when N fertilizer was applied at 120 and 360 kg N/ha for wheat, the soil mineralized nitrogen was 78.6 and 58.1 kg N/ha, representing 65.5% and 16.1% of fertilizer N application, respectively. The lower N application promoted mineralization, making it the majority supply for crop growth (Ju et al., 2002). Experiments in North Central China showed that the nitrogen input by atmospheric deposition for one year was 80–90 kg N/ha, another important source for crop nutrients (Liu et al., 2006b; He et al., 2007; Zhang et al., 2008b). Irrigation water in China often has high levels of N, P, K and trace elements, supporting crop yields and maintaining soil fertility. The mean nitrogen input from irrigation water in the winter wheat–summer maize cropping system in North Central China was 13 kg N/ha (Chen and Zhang, 2006). Biological nitrogen fixation provides another N source in agricultural ecosystem. Lu (1998) pointed out that biological nitrogen fixation was 30 kg N/ha on rice, and Zhu (1992) showed that non-symbiotic nitrogen fixation was 15 kg N/ha in wheat and maize in arid production regions. Sometimes soil test values do not reflect soil nutrient supply capacity. Research showed that P supplied from the soil was always higher than determined by soil test extraction, attributed to root exudation dissolving some unavailable P and large root systems capable of absorbing P from deeper soil (Granssee and Merbach, 2000). It was generally agreed that the available nutrients extracted from the soils by chemical methods provided only a relative value (Tang, 1994; Weigel et al., 2000). Those nutrients coming from the environment and soil, all of which influence fertilizer use efficiency, are called the soil indigenous nutrient supply. The yields in fertilized plots are composed of two parts, one is the yield from the soil indigenous nutrient supply, and the other is from fertilizer application. Making fertilizer recommendations based on soil indigenous nutrient supply has the potential to help reduce the application rates and fertilizer losses, and to improve fertilizer use efficiency.

The *Nutrient Expert for Wheat* is a decision support system being developed by the International Plant Nutrition Institute (IPNI), with the goal of supporting advisors who make fertilizer recommendations to farmers (Pampolino et al., 2012). The *Nutrient Expert for Wheat* system uses site-specific nutrient management (SSNM) principles, which include the use of the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model to determine crop nutrient uptake requirements. SSNM was initially used for rice in the mid-1990s as an alternative approach for dynamic management of nutrients, and to optimize supply and demand of a nutrient within a specific field in a particular cropping season (Dobermann et al., 2002). The QUEFTS model was originally developed by Janssen et al. (1990) and was transformed and validated to estimate the optimum nutrient requirement at a target yield (Smaling and Janssen, 1993; Witt et al., 1999, 2008; Pathak et al., 2003; Liu et al., 2006a; Buresh et al., 2010; Setiyono et al., 2010; Chuan et al., 2012).

The core of the fertilizer recommendation method in *Nutrient Expert for Wheat* is based on yield response and agronomic efficiency (AE). The yield response to N, P or K is the yield gap between NPK plots that received ample nutrients and omission plots when one of the nutrients is omitted. The agronomic efficiency of N, P or K (AEN, AEP or AEK) is the yield increase per unit of fertilizer N,  $\text{P}_2\text{O}_5$  or  $\text{K}_2\text{O}$  applied. Fertilizer recommendation based on yield response and agronomic efficiency is an alternative approach developed for use when soil testing is not available, also considers the N, P and K interactions, and this is an unique feature

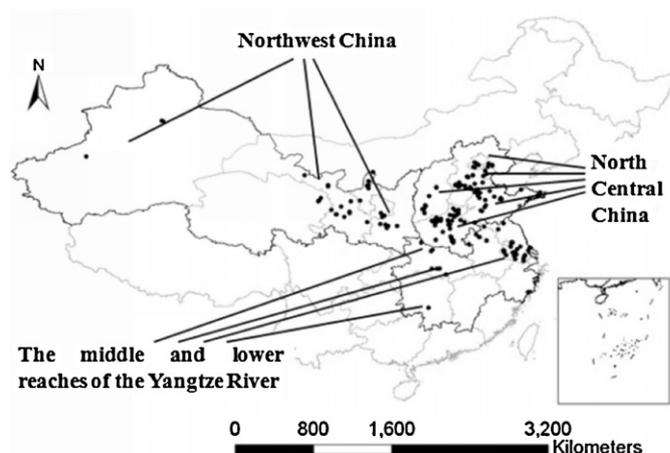


Fig. 1. Geographical distribution of studied locations in North Central China, the middle and lower reaches of the Yangtze River, and Northwest China.

compared with other decision support systems. The determination of fertilizer N requirements from *Nutrient Expert* has been modified to use a target agronomic efficiency and an estimation of yield response to applied N (Buresh and Witt, 2007; Witt et al., 2007; Pampolino et al., 2011). The determination of fertilizer P and K requirements considers the internal nutrient efficiency combined with estimates of attainable yield, nutrient balances, and yield responses from added nutrient within specific fields (Witt et al., 2007; Pampolino et al., 2011). This method utilizes soil indigenous nutrient supply in an attempt to avoid excessive nutrient accumulation in the soil and has been applied with success in rice, maize and wheat crops in some Asian countries (Witt et al., 2007; Buresh et al., 2010; Pampolino et al., 2011; Satyanarayana et al., 2011).

Previously there was no systematic analysis of yield response and agronomic efficiency data across multiple-site and multiple-year from the wheat production areas of China. The objectives of this paper were: (1) to determine yield response, agronomic efficiency and soil indigenous nutrient supply in the main wheat production areas in China; (2) to analyze the inter-relationships among yield response, agronomic efficiency, and soil indigenous nutrient supply; and (3) to develop principles and a scientific basis for fertilizer recommendations using the *Nutrient Expert for Wheat* decision support system.

## 2. Materials and methods

### 2.1. Data source

Datasets for grain yield, fertilizer applications, and N, P and K uptake in mature above-ground plant dry matter were compiled from published literature from 2000 to 2011 in China, along with published and unpublished datasets from the International Plant Nutrition Institute (IPNI)-China Program database. The datasets contained different nutrient management practices including farmers' practice (FP), optimum practice treatment (OPT), long-term field experiments and treatments with different fertilizer rates across wheat-growing environments of China, encompassing North Central (NC), the middle and lower reaches of the Yangtze River (MLYR) and Northwest China (NW) (Fig. 1). The data included a wide range of soil types and climatic conditions (Table 1). The varieties in the experiments were all commonly used in local high yield production and highly represent the great variation in wheat production.

**Table 1**  
Climate characters of experimental sites for wheat production in three regions of China.

Region	Province	Season	n <sup>a</sup>	Precipitation (mm)	Latitude	Longitude	T <sub>min</sub> <sup>b</sup>	T <sub>max</sub> <sup>c</sup>
NC <sup>d</sup>	Hebei	Winter	1305	350–500	38.04	114.51	–8	33
	Henan	Winter	2009	500–900	34.75	113.62	–3	33
	Shanxi	Winter	856	350–700	36.09	111.52	–4	28
	Shandong	Winter	1161	550–950	36.67	116.99	–3	30
	Beijing	Winter	62	550–650	39.90	116.41	–10	33
MLYR <sup>e</sup>	Jiangsu	Winter	616	800–1200	32.06	118.80	3	30
	Hubei	Winter	160	750–1500	30.59	114.31	–4	35
	Anhui	Winter	151	750–1700	31.82	117.23	–1	30
	Hunan	Winter	11	1200–1750	28.23	112.94	4	35
NW <sup>f</sup>	Shaanxi	Winter	312	350–650	34.26	108.94	–10	28
	Ningxia	Spring	232	200–600	38.47	106.26	–9	25
	Gansu	Spring	599	100–300	36.06	103.83	–19	36
	Xinjiang	Winter	11	100–300	43.79	87.63	–20	33

<sup>a</sup> n = the number of the observations.

<sup>b</sup> T<sub>min</sub> = minimum temperature.

<sup>c</sup> T<sub>max</sub> = maximum temperature.

<sup>d</sup> NC = North Central China.

<sup>e</sup> MLYR = the middle and lower reaches of the Yangtze River.

<sup>f</sup> NW = Northwest China.

## 2.2. Overview for field validation

The multiple sites for the experiments were conducted in farmers' fields in Hebei (32 fields) (115°18'E, 37°47'N), Henan (20 fields) (115°13'E, 35°46'N), Shandong (30 fields) (116°24'E, 37°6'N) and Shanxi (10 fields) (111°18'E, 35°48'N) provinces to validate the feasibility of fertilizer recommendations provided by the *Nutrient Expert for Wheat* decision support system. The four provinces were located in North Central China with a winter wheat/summer maize rotation on the fluvo-aquatic or cinnamon soil. Winter wheat was sown after the harvest of maize at the beginning of October and harvested in mid-June of the following year.

Treatments were arranged using a randomized complete block design, where one-farm represented one-replicate design. The size of each treatment ranged from 30 to 40 m<sup>2</sup>. The treatments included a CK (check, no fertilizer applied), a balanced OPT-NE (fertilizer application based on *Nutrient Expert for Wheat* decision support system), a balanced OPT-S (fertilizer application based on soil testing), a FP (fertilizer application based on farmers' traditional practice), and a series of nutrient omission plots, which excluded N, P or K from the OPT-NE treatment. In Hebei province, the application rates in OPT-S were the same as OPT-NE, so only OPT-NE was considered at that location. The fertilizer sources were urea, single superphosphate and potassium chloride. Urea was split applied

two (basal and top dressed by broadcasting at the jointing stage) or three times (basal and top dressed at the jointing stage and filling stage) depending on soil fertility or expected yield response to N, while P and K fertilizers were both broadcast and incorporated as basal before seeding. The rates of fertilizer application were listed in Table 2. Irrigation and other cultural practices were applied using the best local management.

At harvest, three 1 m × 1 m 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 the determination of dry matter weight. Subsamples of straw and grain were collected and analyzed for the determination of N concentration. Details for the analysis and calculation methods of N concentration, total N uptake, AEN, recovery efficiency of N (REN), and gross profit (the gross return above fertilizer cost) were previously described by He et al. (2009). The partial factor productivity of N (PFPN) was calculated as follows:

$$\text{PFPN (kg/kg)} = \frac{\text{grain yield}}{\text{fertilizer N applied}}$$

Data was analyzed using ANOVA with SPSS 13.0 for Windows. Mean separation between different treatments was calculated using least significant difference (LSD) at 0.05 or 0.01 level.

**Table 2**  
Rates of fertilizer application.

Province	Treatment	Fertilizer application (kg/ha)		
		N	P <sub>2</sub> O <sub>5</sub>	K <sub>2</sub> O
Hebei	FP <sup>a</sup>	278 (196–344) <sup>d</sup>	42 (30–68)	24 (0–68)
	OPT-NE <sup>b</sup>	135 (130–150)	52 (50–56)	60 (48–70)
Henan	FP	184 (113–289)	124 (72–225)	127 (27–225)
	OPT-S <sup>c</sup>	210	90	120
	OPT-NE	144 (140–155)	67	70 (60–80)
Shandong	FP	317 (215–400)	161 (75–276)	13 (0–36)
	OPT-S	242	150	60
	OPT-NE	140	78	70 (60–80)
Shanxi	FP	262 (179–502)	110 (19–194)	28 (14–72)
	OPT-S	180	75 (67–90)	76 (60–80)
	OPT-NE	137 (125–140)	67	78 (60–80)

<sup>a</sup> FP = fertilizer application based on farmers' traditional practice.

<sup>b</sup> OPT-NE = fertilizer application based on *Nutrient Expert for Wheat* decision support system.

<sup>c</sup> OPT-S = fertilizer application based on soil testing.

<sup>d</sup> Data in parentheses indicates the range of fertilizer application.

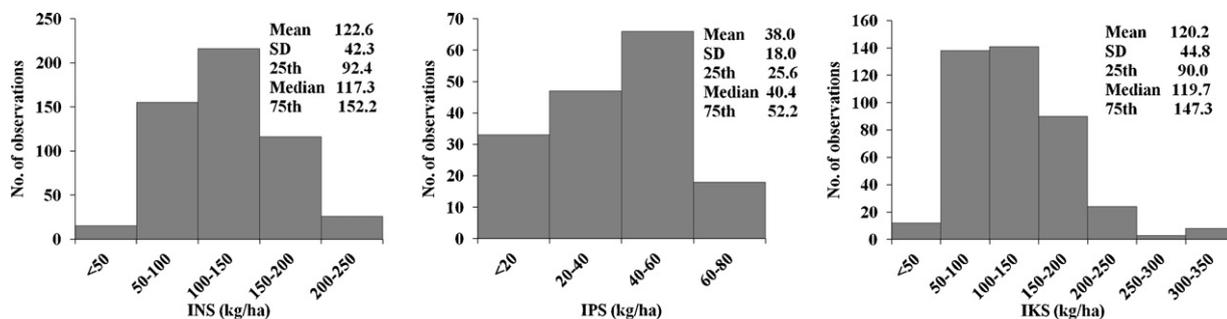


Fig. 2. Frequency distribution of indigenous nutrient supply of N, P and K for wheat. The INS, IPS and IKS mean indigenous N, P and K supply, respectively.

### 3. Results and discussion

#### 3.1. Indigenous nutrient supply

Indigenous nutrient supply was defined as the total amount of a particular nutrient uptake in the omission plots (Janssen et al., 1990). For a specific field, indigenous nutrient supply was an indicator of soil fertility and could be used to estimate fertilizer recommendations for site-specific nutrient management (Dobermann and Cassman, 2002; Dobermann et al., 2003; Cui et al., 2008b). The frequency distribution of indigenous nutrient supply of N, P and K was shown in Fig. 2. There were 40.9% of the observations of indigenous N supply (INS) between 100 and 150 kg N/ha for wheat season. There were 68.9% and 67.1% of the observations of indigenous P supply (IPS) and indigenous K supply (IKS) between 20 and 60 kg P/ha and 50 and 150 kg K/ha, respectively. On average the mean indigenous nutrient supplies for wheat were 122.6 kg N/ha, 38.0 kg P/ha, and 120.2 kg K/ha. These results indicated that the indigenous nutrient supply was relatively high and should be considered when making fertilizer recommendations focused on achieving the optimal nutrient management. The values of INS, IPS and IKS in the wheat season in China were much higher than those determined for Punjab State in Northwest India (i.e., INS 66.3, IPS 15.5 and IKS 79.1 kg/ha) and in Northeast Thailand (i.e., INS 38, IPS 10 and IKS 89 kg/ha) (Naklang et al., 2006; Khurana et al., 2008). Liu et al. (2006a) using the data from 1985 to 1995 in China concluded that the indigenous nutrient supplies for wheat were 54.1 kg N/ha ( $n=345$ ), 14.2 kg P/ha ( $n=74$ ) and 93.4 kg K/ha ( $n=91$ ), respectively. The values in the current study were much higher than previously determined, reflecting over-application of fertilizers in many regions of China, also increasing both residual nutrients and the potential for losses into the environment.

#### 3.2. Yield response and relative yield

Under average growing conditions, crops free of biotic or abiotic stress will show a small yield response in the presence of a

high nutrient supply, and a large yield response with a low nutrient supply. The frequency distribution of wheat yield responses to N, P and K fertilizer application was shown in Fig. 3. The results showed that about 88% of all the observations had a yield response to N less than 3.0 t/ha. There were 62.8% and 72.7% of the yield responses to P and K, respectively, below 1.0 t/ha. The mean yield response to N was 1.7 t/ha, with a range from 0 to 5.9 t/ha. The yield response to P was 1.0 t/ha (ranged from 0 to 4.0 t/ha), and to K was 0.8 t/ha (ranged from 0 to 4.0 t/ha). Clearly, N fertilizer played a primary role in wheat yield increase in this region.

The N, P or K nutrient-limited yield is that achieved where this individual nutrient is absent while all other nutrients are available in ample amounts. The attainable yield is the yield achieved with ample amounts of all nutrients (N, P and K) referred to here as full NPK, OPT or SSNM. The relative yield (GY0/Ya) is the ratio between nutrient-limited yield and attainable yield, suggesting the soil indigenous nutrient supply capacity. A larger relative yield means higher soil indigenous nutrient supply and represents higher soil fertility, while a lower relative yield means lower soil indigenous nutrient supply and lower soil fertility. The results showed that most of the 'GYON/Ya' (the ratio between N-limited yield and attainable yield) and 'GYOP/Ya' (the ratio between P-limited yield and attainable yield) were distributed at 0.6–1.0, and most of 'GYOK/Ya' (the ratio between K-limited yield and attainable yield) was between 0.8 and 1.0 (Fig. 4). The mean relative yields for P and K were higher at 0.85 and 0.90, respectively, while relative yield for N was 0.76, indicating that N was the first nutrient limiting factor for yield, followed by P, and then K.

The yield in the full NPK, OPT or SSNM is higher under a 'favorable' environment than under an 'average' or 'poor' condition. Also, under the same climatic condition, the nutrient-limited yield increases as the attainable yield increases. Additionally, the indigenous nutrient supply (or native soil fertility) could determine the nutrient-limited yield and relative yield. The 25th percentile, median, and 75th percentile of all data for the relationship 'GY0/Ya' could be used as coefficients to estimate the nutrient-limited yield for a given attainable yield and soil fertility class. It assumes

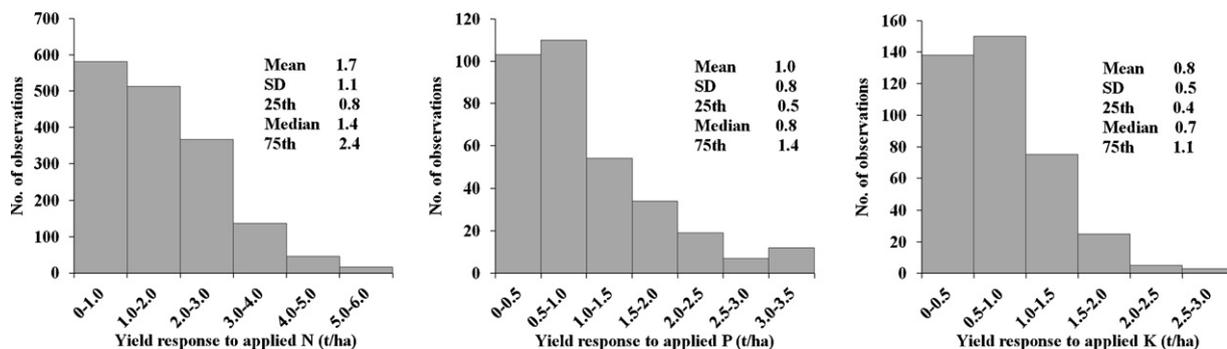
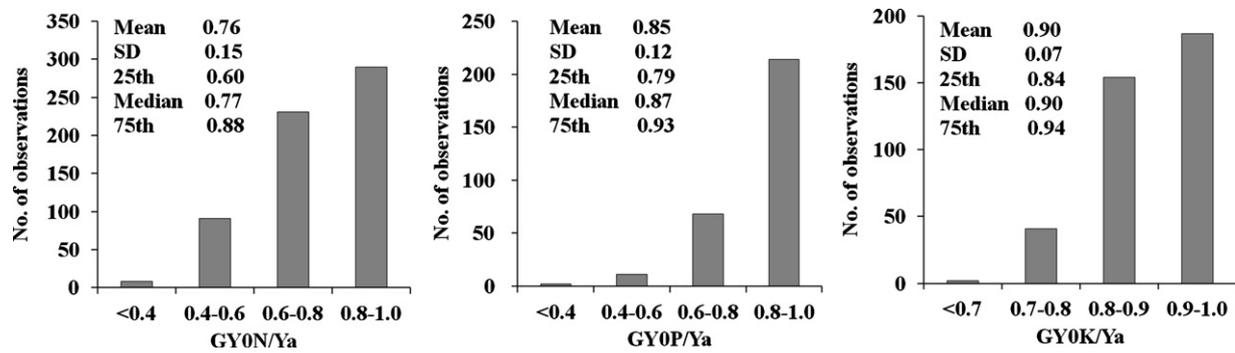


Fig. 3. Frequency distribution of yield responses to applied N, P and K fertilizer for wheat.

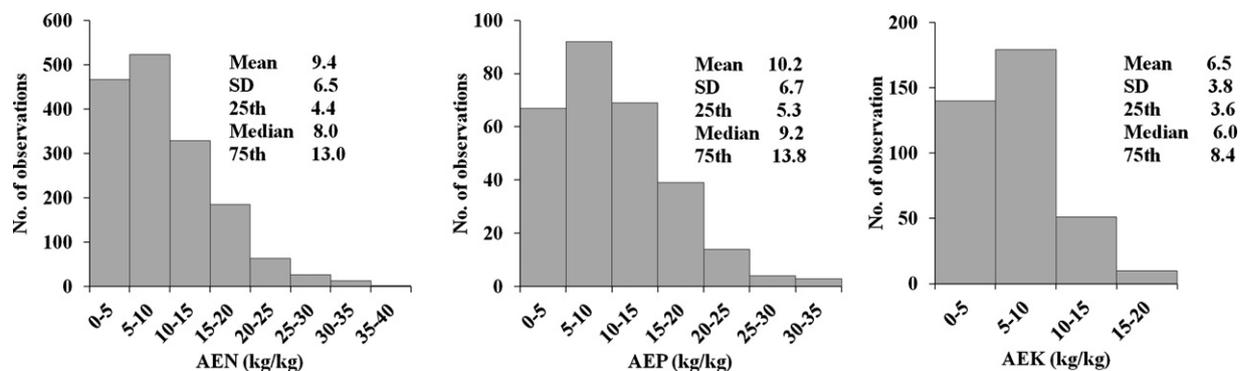


**Fig. 4.** Frequency distribution of nutrient-limited yield to attainable yield of N, P and K for wheat. The relative yield 'GY0N/Ya', 'GY0P/Ya' and 'GY0K/Ya' are the ratios between N, P and K nutrient-limited yield and attainable yield, respectively.

that the median represents soils with 'average' nutrient supply or fertility class, and the 25th and 75th percentile represent 'low' and 'high' nutrient supply or fertility classes, respectively (Pampolino et al., 2012). Results showed that values for 'GY0N/Ya' were 0.60, 0.77 and 0.88 for low, medium, and high N supply, respectively—corresponding to the 25th percentile, median, and 75th percentile of all data ( $n=620$ ) from China. The values for 'GY0P/Ya' were 0.79, 0.87 and 0.93 for low, medium, and high P supply, respectively ( $n=295$ ), and values for 'GY0K/Ya' were 0.84, 0.90 and 0.94 for low, medium, and high K supply, respectively ( $n=406$ ). For example, when given an attainable yield, combined with these coefficients and soil fertility classes, the nutrient-limited yield for N, P and K could be calculated and yield response to N, P and K then could be estimated.

### 3.3. Agronomic efficiency

The frequency distribution of agronomic efficiency for wheat was shown in Fig. 5. The mean agronomic efficiencies for N, P and K were 9.4, 10.2, 6.5 kg/kg respectively, indicating that 61.6%, 55.2% and 83.9% of the observations were lower than 10 kg/kg, respectively. Dobermann (2007) reported that AEN for cereals in developing countries ranged between 10 and 30 kg/kg, and also indicated that AEN could reach an average value >25 kg/kg in a well-managed system with low levels of N use or with low soil N supply. However, compared with developed countries, the nutrient use efficiency in China was still only at the baseline reported by Dobermann (2007), and only reached about 52% of the world average (18 kg/kg) reported by Ladha et al. (2005). Agronomic efficiency of N remains low in China, highlighting the need to improve nutrient management practices in modern production systems (Zhao, 1997; Chen, 2003; Cui, 2005; Gao et al., 2008; Zhang et al., 2008a).



**Fig. 5.** Frequency distribution of agronomic efficiency of N, P and K for wheat. The AEN, AEP and AEK mean agronomic efficiency of N, P and K, respectively.

### 3.4. Relationship between yield response and indigenous nutrient supply

The indigenous nutrient supply ( $y$ ) showed a significant negative exponential relationship with yield response ( $x$ ) ( $P<0.05$ ) (Fig. 6) with 36%, 28% and 43% of the variability for N, P and K, respectively. For a specific field site, when the indigenous nutrient supply was high, the yield response to the applied nutrient was low. These results support the approach that the yield responses could be used as an indicator of soil nutrient supplying capacity.

### 3.5. Relationship between yield response and relative yield

As previously described, when the relative yield (GY0/Ya) is high, the basic soil nutrient supply is high, and the yield response to the applied nutrient is low. Results showed that the coefficients between yield response and relative yield were 0.93 ( $R^2=0.87$ ) for N, 0.90 ( $R^2=0.80$ ) for P and 0.94 ( $R^2=0.88$ ) ( $P<0.05$ ) for K. The relative yield gradually decreased as the yield response increased, and there was an extremely significant negative linear correlation between yield response ( $x$ ) and relative yield ( $y$ ) ( $P<0.01$ ) (Fig. 7).

### 3.6. Relationship between yield response and agronomic efficiency

The yield in an unfertilized plot is mainly supported by the soil indigenous nutrient supply. The yield response between the yield in an unfertilized plot and the target yield is supplied by fertilizer application. The yield response varies as the soil indigenous nutrient supply changes. The agronomic efficiency is also determined by the indigenous nutrient supply, fertilizer application, management practices and climatic conditions. The results showed that there

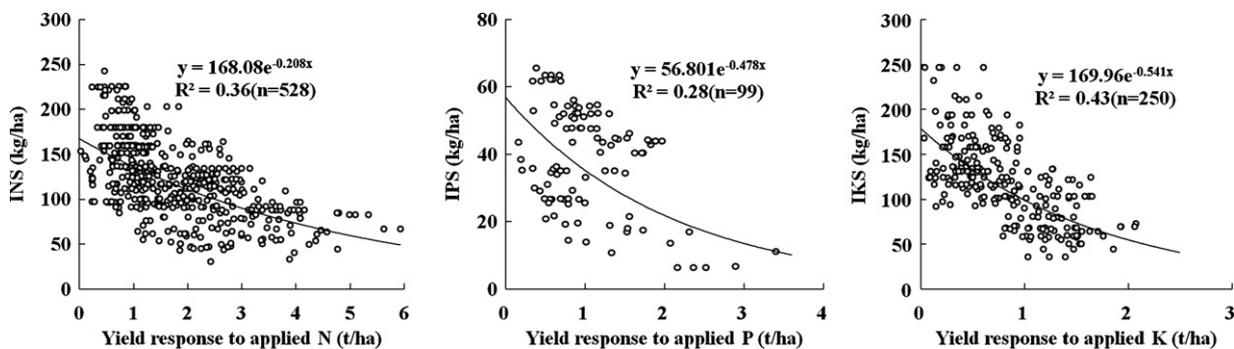


Fig. 6. Relationship between yield response and the indigenous nutrient supply. The INS, IPS and IKS mean indigenous N, P and K supply, respectively.

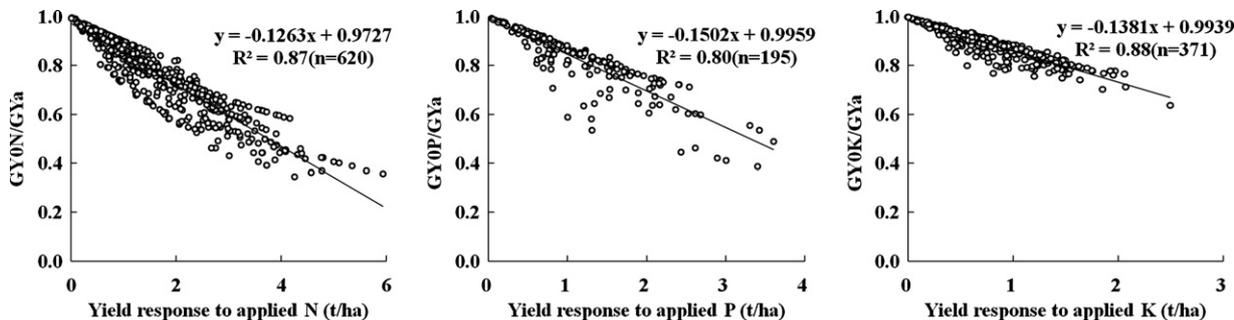


Fig. 7. Relationship between yield response and relative yield for wheat. The relative yield 'GY0N/Ya', 'GY0P/Ya' and 'GY0K/Ya' are the ratios between N, P and K nutrient-limited yield and attainable yield, respectively.

was a significant quadratic relationship between yield response ( $x$ ) and agronomic efficiency ( $y$ ) ( $P < 0.05$ ) (Fig. 8).

Relationship for N:  $y_N = 0.3729x_N^2 + 6.1333x_N + 0.1438$  ( $R^2 = 0.76$ ,  $n = 601$ ).

Relationship for P:  $y_P = 0.5013x_P^2 + 8.3209x_P + 2.3907$  ( $R^2 = 0.65$ ,  $n = 288$ ).

Relationship for K:  $y_K = 1.6581x_K^2 + 9.099x_K + 0.7668$  ( $R^2 = 0.58$ ,  $n = 379$ ).

where  $x_N$ ,  $x_P$  and  $x_K$  were the yield response to N, P and K, and  $y_N$ ,  $y_P$  and  $y_K$  were the agronomic efficiency to N, P and K, respectively.

Initially the agronomic efficiency for a nutrient increased with yield response increasing, but the amount of increase became smaller as the yield response became larger. A lower yield response indicates higher soil indigenous nutrient supply or higher soil fertility, resulting in lower agronomic efficiency. In contrast, a larger yield response means lower soil nutrient supply and relatively higher agronomic efficiency.

### 3.7. Principles of fertilizer recommendation and field validation

Based on the above analysis, the principles of nutrient recommendations were formed and were incorporated as part of the *Nutrient Expert for Wheat* decision support system (Chuan et al., 2012; He et al., 2012; Pampolino et al., 2012). Nitrogen fertilizer recommendations were calculated from yield response divided by agronomic efficiency. For P and K, both the nutrient from yield gain and maintenance of soil fertility were considered. The nutrient requirements for yield gain were calculated from the yield response and agronomic efficiency, and the maintenance of soil fertility was calculated from the nutrient removal estimated by QUEFTS model (Chuan et al., 2012). Trace elements (such as Zn, Fe, Mn and Mg) were applied if a soil test was showing a deficiency. Multiple points (total 92 fields) of field validation were conducted across North Central China in Hebei, Henan, Shandong and Shanxi provinces in 2010–2011, respectively, to test the feasibility of *Nutrient Expert* decision support system. The OPT-NE plots increased grain yield by 3.7%, 0.1% and 1.1% compared with that in FP plots in Hebei, Henan and Shandong provinces. This occurred with a net reduction

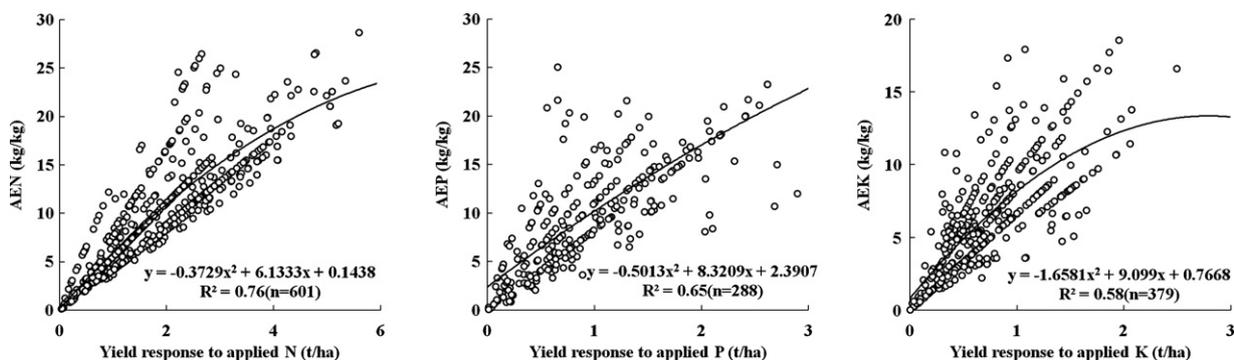
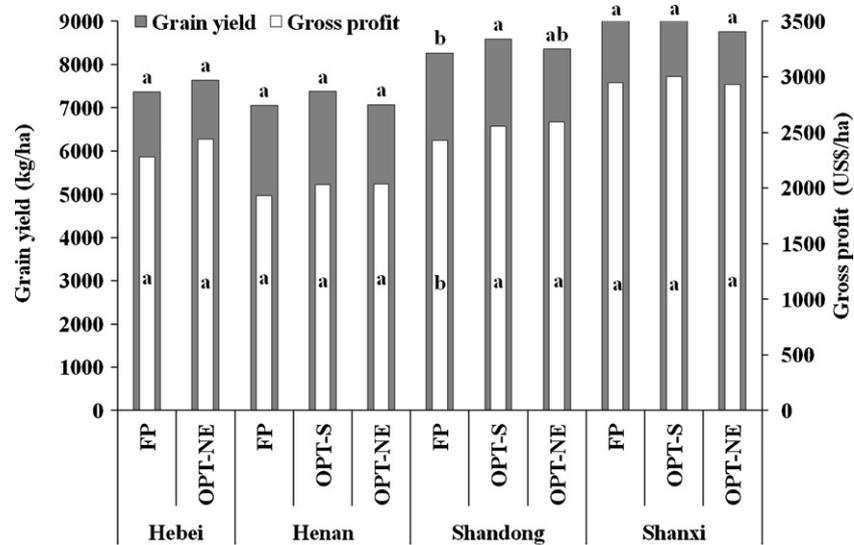
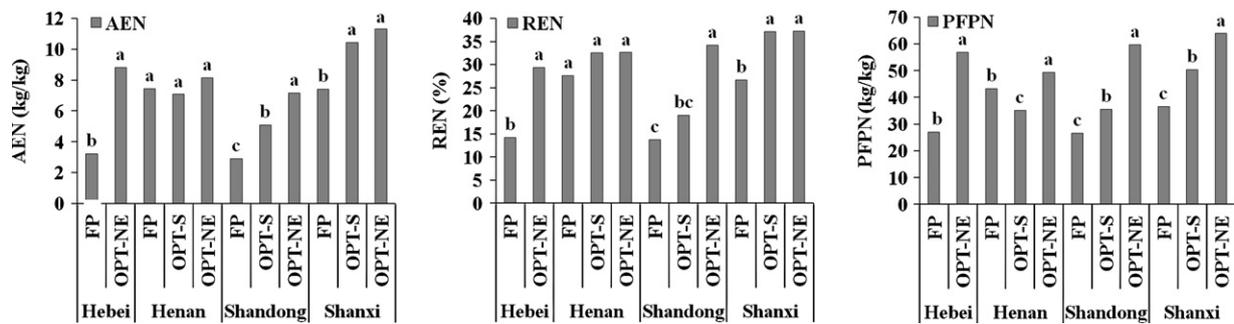


Fig. 8. Relationship between yield response and agronomic efficiency for wheat. The AEN, AEP and AEK mean agronomic efficiency of N, P and K, respectively.



**Fig. 9.** The grain yield and gross profit in Hebei, Henan, Shandong and Shanxi provinces in 2010–2011. The fertilizer rates in OPT-NE, OPT-S and FP were based on *Nutrient Expert for Wheat* decision support system, soil testing and farmers' traditional practice, respectively. The gross profit was the gross return above fertilizer cost. The prices of wheat in Hebei, Henan, Shandong and Shanxi were 2.2, 2.0, 2.12 and 2.3 RMB/kg, respectively; Prices for N, P<sub>2</sub>O<sub>5</sub> and K<sub>2</sub>O were 5.0, 6.3 and 7.3 RMB/kg in Hebei, 4.0, 5.6 and 5.0 RMB/kg in Henan, 4.4, 4.8 and 5.3 RMB/kg in Shandong, 5.0, 6.3 and 7.3 RMB/kg in Shanxi province, respectively. 1 US\$ = 6.3 RMB. Different letters above the columns mean significant difference ( $P < 0.05$ ).



**Fig. 10.** The agronomic efficiency of N (AEN), recovery efficiency of N (REN) and partial factor productivity of N (PFPN) in Hebei, Henan, Shandong and Shanxi provinces in 2010–2011. Different letters above the columns mean significant difference ( $P < 0.05$ ).

in fertilizer N application in Hebei by 51.4%, Henan by 21.7% and Shandong by 55.8%, and gross profit improvement for the three provinces of 158, 103 and 168 US\$/ha, respectively (Fig. 9). However, in Shanxi province, with N and P fertilizer application reduced by 47.7% and 39.1%, it slightly decreased the yield ( $P > 0.05$ ) while maintaining the gross profit. Compared to OPT-S, the yield in OPT-NE was slightly lower, but the gross profit was not significantly decreased ( $P > 0.05$ ) or even improved. The AEN and REN in Hebei, Shandong and Shanxi were significantly enhanced, respectively ( $P < 0.05$ ) (Fig. 10). The averaged AEN in FP ranged from 2.9 to 7.4 kg/kg, and in OPT-NE ranged from 7.2 to 11.3 kg/kg, which were 1.1–2.8 times of FP. The REN in OPT-NE was improved by 5.0–20.5 percentage points compared to FP. The PFPN was significantly improved in OPT-NE. Compared to OPT-S, the AEN, REN and PFPN in OPT-NE were significantly increased in most sites ( $P < 0.05$ ).

#### 4. Conclusions

Based on the data from the literature over the years 2000–2011, it was found that the mean yield responses of wheat to N, P and K were 1.7, 1.0 and 0.8 t/ha in China, respectively. Nitrogen was the nutrient most limiting yield, followed by P and then K. The indigenous nutrient supplies for wheat were 122.6 kg N/ha, 38.0 kg P/ha, and 120.2 kg K/ha. The mean agronomic efficiencies were 9.4, 10.2 and 6.5 kg/kg for N, P and K, respectively.

In this study we determined that there was a significant negative exponential relationship between yield response and soil indigenous nutrient supply ( $P < 0.05$ ), and a significant negative linear correlation between yield response and relative yield ( $P < 0.05$ ). We also demonstrated a quadratic equation between yield response ( $x$ ) and agronomic efficiency ( $y$ ) ( $P < 0.05$ ). Based on the above analysis, the principles of nutrient recommendations were formed and incorporated as part of the *Nutrient Expert for Wheat* decision support system. Field validation based on yield response and agronomic efficiency showed a trend to increase both grain yield and gross profit, and AEN, REN and PFPN were all improved in most sites. It was concluded that *Nutrient Expert for Wheat* could be used as an alternative method of soil testing when making fertilizer recommendation.

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