Yield Gaps, Indigenous Nutrient Supply, and Nutrient Use Efficiency of Wheat in China

Xiaoyan Liu, Ping He,* Jiyun Jin, Wei Zhou, Gavin Sulewski, and Steve Phillips

ABSTRACT

Great advances in food production have been made in China, but the continuous increase of nutrient inputs has caused a series of environmental problems. Nutrient management for crops must be improved. Yield gaps, indigenous nutrient supplies, and nutrient use efficiencies (NUEs) must be assessed to design management strategies for further yield increase. In this study, data from 1022 field experiments with wheat (*Triticum aestivum* L.) conducted between 2000 and 2008 in north central China, the middle and lower reaches of the Yangtze River, and northwest China were analyzed. Treatments in these experiments consisted of a check without fertilizer use, an optimum nutrient application, the farmers' practice, and a series of nutrient omission treatments. The results showed that gaps between attainable yields and yields in experimental plots with farmers' practices averaged 0.76 Mg ha^{-1}. Indigenous nutrient supplies of N, P, and K averaged 133.0, 30.2, and 131.7 kg ha^{-1}, respectively, in the regions studied. On a national scale and under optimum fertilization, agronomic efficiency of N, P, and K were 9.8, 19.2, and 7.2 kg kg^{-1}, while recovery efficiencies were 37.9, 19.0, and 27.0%, respectively. Compared with values obtained 10 yr previous, agronomic efficiencies and recovery efficiencies determined between 2000 and 2008 were lower but also lower than world averages. Successive inputs of large amounts of nutrients significantly increased the indigenous nutrient supply and therefore are contributing to lower NUE because recommendations for N, P, and K have not been adjusted downward in China.

China is a country with a large population and limited arable lands per capita (0.09 ha per capita) (Huang et al., 2010) compared with the world average of 0.23 ha per capita (Pimentel, 2006). To sustain China's population, either crop yield per unit area must increase by 20% within the next 10 yr if the agricultural land decreases at a rate of 1% annually (Zhang et al., 2007), or crop yield per unit area must increase by 10% if the sown area remains steady (Jin et al., 2006). Producing more food per unit of land requires the development and application of new technology and a further intensification of management. Commercial fertilizers are needed to avoid nutrient depletion and ensure soil quality. Policy-driven increases in fertilizer use have contributed to rising crop yields to sustain food security in China. Overapplication of N fertilizer, however, has been a common practice in wheat–maize (*Zea mays* L.) and wheat–rice (*Oryza sativa* L.) rotation systems (Liu et al., 2005a; Zhao et al., 2006; He et al., 2009) and has led to nutrient imbalances, inefficient use, and large losses to the environment, with impacts on air and water quality, biodiversity, and human health (Cai et al., 2002; Zhu and Chen, 2002; Liu et al., 2005b; Ju et al., 2009).

Improved nutrient management practices are urgently needed to maximize wheat yield and maintain soil fertility while minimizing environmental impacts. To improve nutrient management, it is useful to know the potential yield and the gap between the potential yield and the actual yields obtained by growers. Inefficient crop management may cause the actual yield to deviate from the potential yield—this difference is called the *yield gap* (van Ittersum and Rabbinge, 1997; Tittonell et al., 2008; Neumann et al., 2010). Lobell et al. (2009) used three main techniques (model simulations, field experiments and yield contests, and maximum farmer yields) to assess the yield potential and yield gaps. Field experimentation provides a direct measure of the yield potential that integrates crop management practices designed to minimize many yield-limiting factors, such as nutrient deficiencies or toxicities, damage from insects, pests, and disease, and competition from weeds.

In addition, improved understanding is needed of the crop yield response to nutrients, NUE, and the indigenous nutrient supply from soil and environmental sources. Differences in nutrient response are due to the variability in the crop demand and the soil nutrient supply and losses (Cui et al., 2008). Indigenous nutrient supply can be defined as the cumulative quantity of nutrients from all nonfertilizer sources that are found in the soil solution surrounding the root system (Dobermann

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Abbreviations: AE, agronomic efficiency; FP, farmers' practice; IE, internal efficiency; INS, indigenous nitrogen supply; IKS, indigenous potassium supply; IPS, indigenous phosphorus supply; MLYR, middle and lower reaches of the Yangtze River; NC, north central; NUE, nutrient use efficiency; NW, northwest; OPT, optimum nutrient treatment; PFP, partial factor productivity; PNB, partial nutrient budget; RE, recovery efficiency.

et al., 2003). Nutrient use efficiency is an important index not only for fertilizer recommendation at the field scale but also for forecasting fertilizer demand at the regional and national scales. It is receiving increased attention today because of growing pressure for agriculture to minimize negative environmental impacts. Internal efficiency (IE), partial factor productivity (PFP), agronomic efficiency (AE), recovery efficiency (RE), and the partial nutrient budget (PNB) of applied nutrients are frequently used in agronomic research to assess the NUE (Cassman et al., 2002; Dobermann, 2007; Snyder and Bruulsema, 2007). Dobermann (2007) reported that 55 to 65 kg kg^{-1} is the optimal range of IE_N for balanced nutrition at high yield levels, $AE_N > 30$ kg kg^{-1} and $PEP_N > 60$ kg kg^{-1} in well-managed systems. A review of worldwide data on the RE of cereal crops from researcher-managed experimental plots reported that single-year fertilizer N recovery efficiencies averaged 65% for maize, 57% for wheat, and 46% for rice (Ladha et al., 2005). A PNB is used to evaluate the sustainability of a cropping system. The PNB is >1 in nutrient-deficient systems (fertility improvement), <1 in nutrient-surplus systems (underreplacement), and slightly less than 1:1 in sustainable systems (Snyder and Bruulsema, 2007).

In China, many experiments have been performed to study yield gaps and NUEs, such as RE and AE (Liu et al., 2006; Zhang et al., 2007; Wang et al., 2010), but there is lack of a systematic analysis of the yield gaps among the attainable yields in an experimental plot (Y_a), yields under farmers' practices (Y_f), and yields without nutrients applied (Y_{ck}), the NUEs of N, P, and K, and the indigenous nutrient supply for wheat in the different production regions in China. The objectives of this study were to: (i) quantify the yield gap between Y_a and Y_f, (ii) evaluate the wheat grain yield responses to applied N, P, and K, (iii) calculate the NUE, including IE, PFP, AE, RE, and PNB of N, P, and K, and (iv) determine the indigenous soil fertility, including the indigenous N supply (INS), indigenous P supply (IPS), and indigenous K supply (IKS) in different wheat production regions of China. The results from this study should help optimize nutrient management practices for wheat in China, which in turn could increase the wheat yield, improve NUE, and protect the environment.

MATERIALS AND METHODS

Site Characteristics

In China, winter wheat and spring wheat are both grown, although winter wheat accounts for >90% of China's total production. Spring wheat is mainly planted in the northwest (NW) and northeast regions, and winter wheat is mainly planted in north-central (NC) China and the middle and lower reaches of the Yangtze River (MLYR) (Fig. 1). The area sown to wheat in NC China and the MLYR occupies around 55 and 24% of the national total, respectively, and produces about 62 and 23% of the national wheat output (Editorial Board of China Agricultural Yearbook, 2008). Field experiments were conducted between 2000 and 2008 in the three production regions. Each region represents a large area with relatively similar soils, climatic conditions, and cropping systems (Table 1). North-central

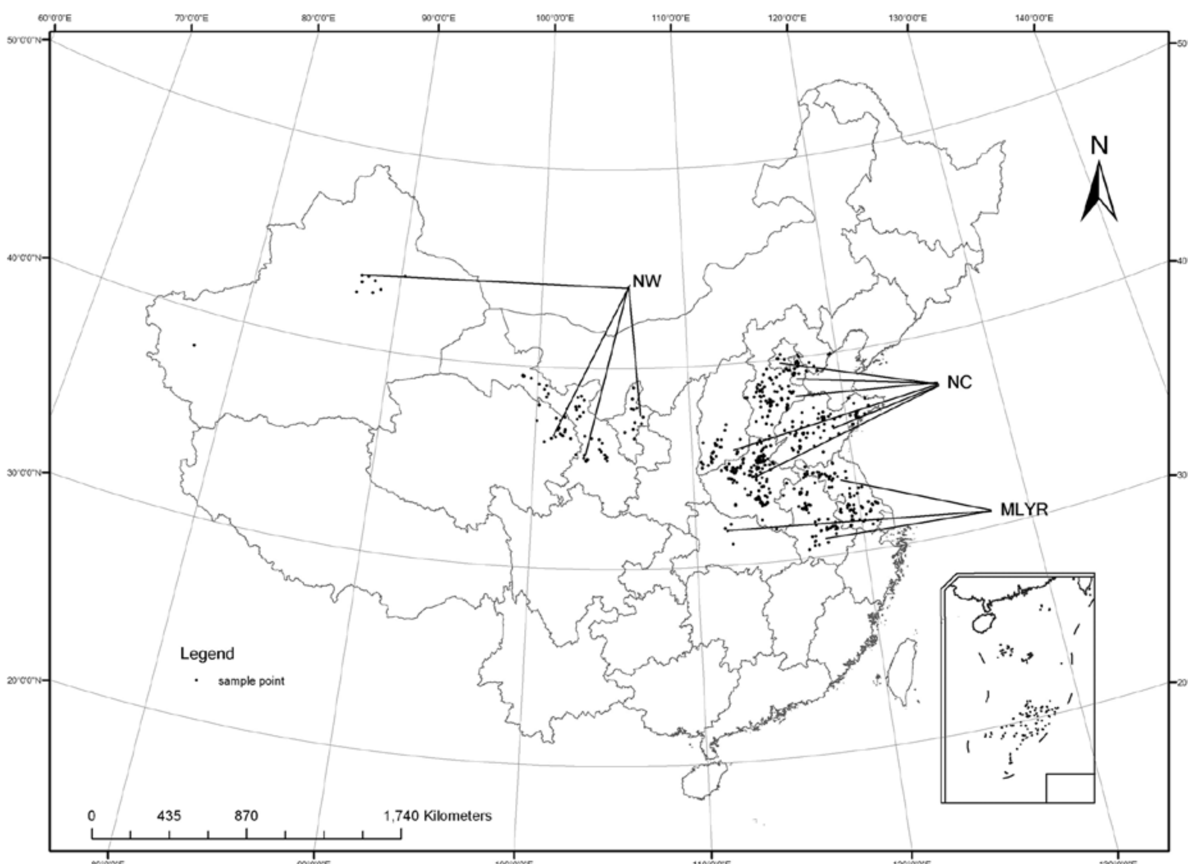

Fig. 1. Geographical distribution of studied locations in north-central (NC) China, the middle and lower reaches of the Yangtze River (MLYR), and northwest (NW) China.

Table 1. Summary of experimental sites for wheat production in three regions in China.

Region†	Province	Wheat season	Precipitation	Growth duration	Main soil types	Altitude	Experiments
			mm	d		m	no.
NC China	Henan	winter	500–900	220–240	Flavo-aquic soil, Cinnamon soil	10–100	268
	Shandong	winter	550–950	220–250	Flavo-aquic soil, Cinnamon soil, Brown soil	0–100	108
	Shanxi	winter	350–700	230-–250	Cinnamon soil	50–400	72
	Hebei	winter	350–500	230–260	Cinnamon soil, Flavo-aquic soil	20–100	98
	Tianjin	winter	550–650	230–260	Flavo-aquic soil, Saline-alkali soil	0–50	46
	Beijing	winter	550–650	230–260	Flavo-aquic soil	25–50	3
MLYR	Jiangsu	winter	800–1200	220–230	Yellow brown soil, Paddy soil, Flavo-aquic soil	0–50	207
	Anhui	winter	750–1700	220–240	Yellow brown soil, Paddy soil	10–50	89
	Hubei	winter	750–1500	200–220	Yellow brown soil, Paddy soil	50–100	4
NW China	Gansu	spring	100–300	120–130	Flavo-aquic soil, Desert soil	1500–1800	50
	Ningxia	spring	200–600	120–130	Irrigation-silting soil	1000–1300	22
	Qinghai	spring	100–400	120–130	Gray calcareous soil, Chestnut soil	1800–2500	46
	Xinjiang	spring	100-500	120–130	Chestnut soil	800–1300	9

† NC, north central; MLYR, middle and lower reaches of the Yangtze River; NW, northwest.

China is dominated by a temperate climate and a winter wheat–maize annual rotation. The MLYR has a temperate to subtropical humid climate and a predominant rice–wheat rotation system. Northwest China has a continental climate and a continuous spring wheat cropping system.

Data Source

Yield data were obtained from field experiments conducted by the International Plant Nutrition Institute (IPNI) China Program and other published studies in different wheat production regions of China (Table 1; Fig. 1). Each of the published studies met the following criteria: (i) reported on well-designed, randomized experiments that were conducted on either a research station or farmers' fields in China; (ii) included a refereed journal, peer-reviewed proceedings, or master's or doctoral thesis; (iii) had treatments that included full N, P, and K balanced fertilization and omission plots for N, P, and K; and (iv) reported data with mean values as numerical or graphical data. In the latter case, graphical data were converted to numerical data using the Dagra software package (Blue Leaf Software, Hamilton, New Zealand).

Field experiments conducted by IPNI mainly included experiments with an optimum nutrient (OPT) treatment based on soil testing and target yields (He et al., 2009), a check without any fertilizer applied, and a series of nutrient omission treatments consisting of an OPT–N, OPT–P, OPT–K and farmers' practice (FP), or a series of nutrient omission treatments consisting of FP–N, FP–P, or FP–K. The FP treatment was designed based on farmers' practices and managed at the experimental sites. The OPT treatment consisted of N, P, and K applied in accordance with soil test levels and the yield goal. An OPT–N refers to P and K applied but no N. Except for the fertilizer application amount and method, sowing, irrigation, insect and weed control, tillage, and other management activities in the OPT treatments were conducted according to the FP treatment. Treatments from published studies were comprised of an OPT treatment with the highest yield and N, P, and K omission plots with other nutrients amply supplied (OPT–N, OPT–P, and OPT–K). The plot size ranged from 20 to 50 m^2 depending on location. These experiments covered a wide range of soils, crop cultivars, agronomic practices, cropping systems, and climatic conditions. At harvest, the yields and nutrient uptake of the different treatments were analyzed.

Quantification of Yield Gaps, Nutrient Use Efficiencies, and Statistical Analysis

Yield potential can be defined and measured in a variety of ways (Lobell et al., 2009). In this study, we defined yield potential as Y_a given the best nutrient management practices under experimental conditions, and yield gaps as the difference between the yield potential and the average farmers' yields across some specific spatial and temporal scale of interest. To aid comparison of different studies, we denote the methods used to measure yield gaps; Y_a and Y_f were obtained from the OPT and FP treatments, respectively.

The farmer-based yield gap (YG_f) is the yield difference between Y_a and Y_f:

$$YG_f = Y_a - Y_f \quad [1]$$

The check-based yield gap (YG_{ck}) is the yield difference between Y_a and Y_{ck}:

$$YG_{ck} = Y_a - Y_{ck} \quad [2]$$

Wheat grain yield responses to applied N, P, and K were calculated from the differences between an OPT treatment and the N, P, or K omission plot (OPT–N, OPT–P, or OPT–K). For example, yield response to N = grain $yield_{(OPT)}$ – grain $yield_{(OPT-N)}$.

Internal efficiency has been defined as the amount of grain yield produced per kilogram of nutrient accumulation in the aboveground plant dry matter expressed on an oven-dry basis. The PFP is calculated in units of crop yield per unit of nutrient applied. Agronomic efficiency is calculated in units of yield increase per unit of nutrient applied. It more closely reflects the impact of applied fertilizer on the yield because it measures the amount of grain yield gained by the nutrient input (Snyder and Bruulsema, 2007). Recovery efficiency is defined as the increase in crop uptake of a nutrient in the aboveground parts of the plant in response to application of that nutrient. Like AE, it can be measured when a nutrient omission plot has been implemented. The PNB is used to evaluate the sustainability of a cropping system and is calculated in units of nutrient uptake by the harvested portion per unit of nutrient applied (Snyder and Bruulsema, 2007). This approach has been successfully used in recent studies of crop management practices (Cassman et al., 1996; Witt and Dobermann, 2002; Pathak et al., 2003). Measurements of the aforementioned indices help to compare NUE in different environments and evaluate different management strategies. To estimate the NUE of wheat, IE, PFP, AE, RE, and PNB were calculated from the OPT and nutrient omission treatments (OPT–N, OPT–P, and OPT–K) using

$$\mathrm{IE}_X = \frac{\text{grain yield}_{(\mathrm{OPT})}}{\text{nutrient}(X)\ \text{uptake by aboveground plant}} \quad [3]$$

$$\mathrm{PFP}_X = \frac{\text{grain yield}_{(\mathrm{OPT})}}{\text{applied fertilizer } X} \quad [4]$$

$$\mathrm{AE}_X = \frac{\text{yield}_{(\mathrm{OPT})} - \text{yield}_{(\mathrm{OPT}-X)}}{\text{applied fertilizer } X} \quad [5]$$

$$\mathrm{RE}_X = \frac{X\ \text{uptake}_{(\mathrm{OPT})} - X\ \text{uptake}_{(\mathrm{OPT}-X)}}{\text{applied fertilizer } X} \quad [6]$$

$$\mathrm{PNB}_X = \frac{X\ \text{uptake by grain and straw}_{(\mathrm{OPT})}}{\text{applied fertilizer } X} \quad [7]$$

where X is N, P, or K. It should be noted that almost all straw was also removed in most field experiments. Therefore, the PNB_X was calculated as the total nutrient removal by grain and straw.

The indigenous nutrient supply is defined as the total amount of a particular nutrient that is available to the crop from the soil during a cropping cycle when other nutrients are nonlimiting (Witt and Dobermann, 2002). The indigenous nutrient supply was estimated from the nutrient omission plots (OPT–N, OPT–P, and OPT–K). For example, the indigenous N supply was calculated as the wheat N uptake in the OPT–N treatment.

A meta analysis was conducted to analyze the yield gaps ($\mathrm{YG_f}$ and $\mathrm{YG_{ck}}$) and yield responses to applied N, P, and K using Revman 5.0 software (developed by the Cochrane Collaboration, Oxford, UK). For each region, the weighted mean difference (WMD) in yield for the OPT vs. FP treatments and for the OPT treatment vs. the N, P, and K omission plots (OPT–N, OPT–P, and OPT–K) was computed, and a summary was obtained as a weighted average of the individual ones by means of the random effects model. If there was statistically significant heterogeneity for yield gaps or the yield response to nutrients among three regions in China, the studies were subdivided into two time periods in each region to test the difference between the earlier (2000–2004) and more recent experiments (2005–2008). The Cochran Q test was used to test for heterogeneity. A P value <0.1 by the Cochran Q test indicated statistically significant heterogeneity. Estimates of effect size were considered to be significantly different from zero if their 95% CIs did not overlap with zero.

The means of the indigenous nutrient supply and the indices of NUE (IE, PFP, RE, AE, and PNB) in the three wheat growing regions were compared using SPSS 13.0 for Windows (SPSS, Chicago). For data meeting the normality or near-normality and variance homogeneity assumptions, the means were compared using LSD at the 0.05 level of probability whenever a significant F test was observed in the ANOVA. For data that did not meet the normality or near-normality and variance homogeneity assumptions, however, and was not successful in achieving the desired end after transformation (logarithmic, square-root, arcsine, inverse transformation, etc.), the means was analyzed using the Kruskal–Wallis test for k independent samples and the difference between two regions was analyzed using the Mann–Whitney U test for two independent samples in the nonparametric test.

RESULTS AND DISCUSSION

Yield Gaps

The value of Y_a obtained in the OPT treatments averaged 7.18 Mg ha^{-1} in NC China, 6.56 Mg ha^{-1} in the MLYR, and 5.47 Mg ha^{-1} in NW China (Table 2). Except for nutrient management practices, rainfall is the limiting factor for wheat yields in NC and NW China, while in the MLYR, the joint effect of low radiation and high temperature is the major limiting factor

Table 2. Yield gaps between attainable yield (Y_a) and yield without fertilizer application (Y_{ck}) in experimental plots and 95% confidence interval (CI) in different production regions of China.

Region†	Y_a			Y_{ck}				
	Mean	SD	*n*	Mean	SD	*n*	Weight	Mean differenceIV‡, Random, 95%CI
	—— Mg ha^{-1} ——			—— Mg ha^{-1} ——			%	
NC China	7.18	1.31	594	4.53	1.21	133	33.9	2.65 (2.42, 2.88)
MLYR	6.56	1.36	301	2.79	1.07	80	33.6	3.77 (3.49, 4.05)
NW China	5.47	1.42	127	3.73	1.07	38	32.6	1.74 (1.32, 2.16)
Total (95% CI)			1022			251	100.0	2.73 (1.70, 3.76)
Heterogeneity	P < 0.00001							
Test for overall effect	P < 0.00001							

† NC, north central; MLYR, middle and lower reaches of the Yangtze River; NW, northwest.

‡ IV, inverse variance.

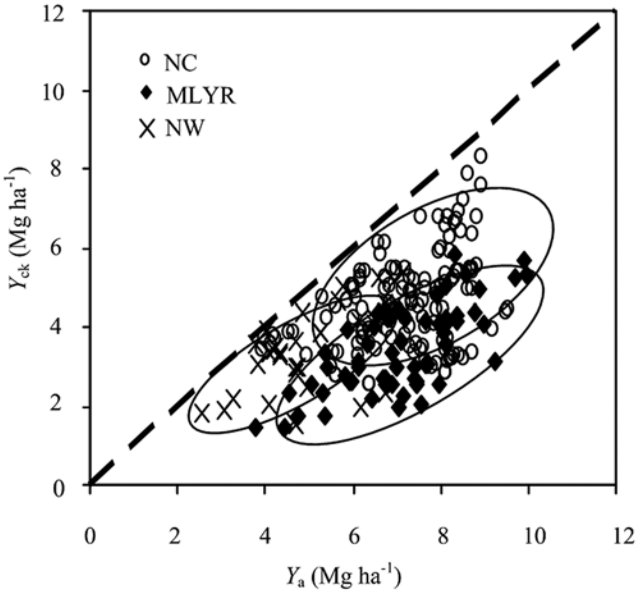

Fig. 2. Comparison of attainable yield in experimental plots (Y_a) and yield without fertilizer application (Y_{ck}) in north-central (NC) China, the middle and lower reaches of the Yangtze River (MLYR), and northwest (NW) China. The broken line represents the same Y_a and Y_{ck}.

(Han and Li, 2004; Wu et al., 2006). The meta analysis showed that there was no significant difference for YG_{ck} between 2000 to 2004 and 2005 to 2008 in the three regions (data not shown, $P > 0.05$). Relatively narrow YG_{ck} values were observed for NC (2.65 Mg ha^{-1}) and NW China (1.74 Mg ha^{-1}), while a large yield gap (3.77 Mg ha^{-1}) was observed for the MLYR (Table 2, $P < 0.05$). Figure 2 shows that YG_{ck} varied among regions, with fertilizer omission having its largest impact on yield in the MLYR. In this study, the Y_{ck} averaged 3.86 Mg ha^{-1} in China, which was about 57% of Y_a and 65% of Y_f (i.e., 43% increase in Y_a and 35% increase in Y_f was attributable to optimal nutrient management strategies in China). The fertilizer contribution to yield values were similar to the data (at least 30–50%) from several long-term studies in the United States, United Kingdom, and the tropics reported by Stewart et al. (2005).

The YG_f was 0.79 Mg ha^{-1} in NC China, 0.69 Mg ha^{-1} in the MLYR, and 0.74 Mg ha^{-1} in NW China across all farm practices and locations, but the difference was not statistically significant ($P > 0.05$, Table 3). Although the Y_{ck} was lower in the MLYR, the YG_f was smaller after fertilization due to the high awareness of science and technology among its farmers and rapid economic development in the MLYR region (Magen, 2007). The average YG_f in China was 0.76 Mg ha^{-1}, which was about 12% of Y_f. In other words, even with farmers' practices, the yield gap was narrowed to about 12% through a balanced optimal treatment. The value of YG_f in this study was mainly caused by nutrient management factors such as nutrient deficiency or imbalanced nutrition. For example, excessive N fertilization was also common in the MLYR and NW China (Fig. 3 and 4). Cases of under- and overapplication of P by farmers were found in NC and NW China, respectively. Underapplication of K was more serious throughout China, and its application by farmers was less than half of the OPT rates for wheat. In the 25 farmer fields in a field experiment in NW China, no K fertilizer was applied to spring wheat (Fig. 4).

The lower wheat YG_f in China was similar to the value calculated by Neumann et al. (2010). But the YG_f in China is reported to be less than that in Mexico (2.5 Mg ha^{-1}, 29% of Y_a) (Lobell et al., 2009). Rejesus et al. (1999) described a similar overshoot in fertilizer application (251 kg N ha^{-1}) for intensive wheat systems in Mexico. The main reason for the lower YG_f in this study, therefore, may be that OPT treatments were not combined with other high-yield management such as disease and insect control and selection of more productive cultivars. The YG_f would be increased if optimum nutrient management were combined with other high-yield cultivation technologies (high-yielding cultivars with stress tolerance, optimum sowing date, optimum water content, etc.). In China, the availability of cheap labor and a series of beneficial policies promoting soil testing and fertilization recommendations, agricultural production subsidies, and a continued high wheat price were all driving forces for farmers to pursue high yields and low yield gaps in recent years.

Yield Responses to Nutrients and Indigenous Nutrient Supply

As an overall summary of the results, the yield responses to N, P, and K for wheat across regions were 1.84, 0.78, and 0.74 Mg ha^{-1}, respectively (Table 4), and the meta analysis showed no significant difference for yield response to N, P, and K between 2000 to 2004 and 2005 to 2008 in the three regions (data not shown, $P > 0.05$). The yield response to N for wheat differed among different regions, following the order: the MLYR > NC China > NW China. The importance of N to crop yields has also been the primary cause for a continued

Table 3. Yield gaps between attainable yield (Y_a) and farmers' yield (Y_f) in experimental plots and 95% confidence interval (CI) in different production regions of China.

Region†	Y_a			Y_f			Weight	Mean difference IV‡, Random, 95%CI
	Mean	SD	*n*	Mean	SD	*n*		
	—— Mg ha^{-1} ——			—— Mg ha^{-1} ——			%	
NC China	7.18	1.31	594	6.39	0.86	149	68.5	0.79 (0.62, 0.96)
MLYR	6.56	1.36	301	5.87	1.12	75	23.5	0.69 (0.39, 0.99)
NW China	5.47	1.42	127	4.73	1.26	31	8.0	0.74 (0.23, 1.25)
Total (95% CI)			1022			255	100.0	0.76 (0.62, 0.91)
Heterogeneity	$P = 0.85$							
Test for overall effect	$P < 0.00001$							

† NC, north central; MLYR, middle and lower reaches of the Yangtze River; NW, northwest.

‡ IV, inverse variance.

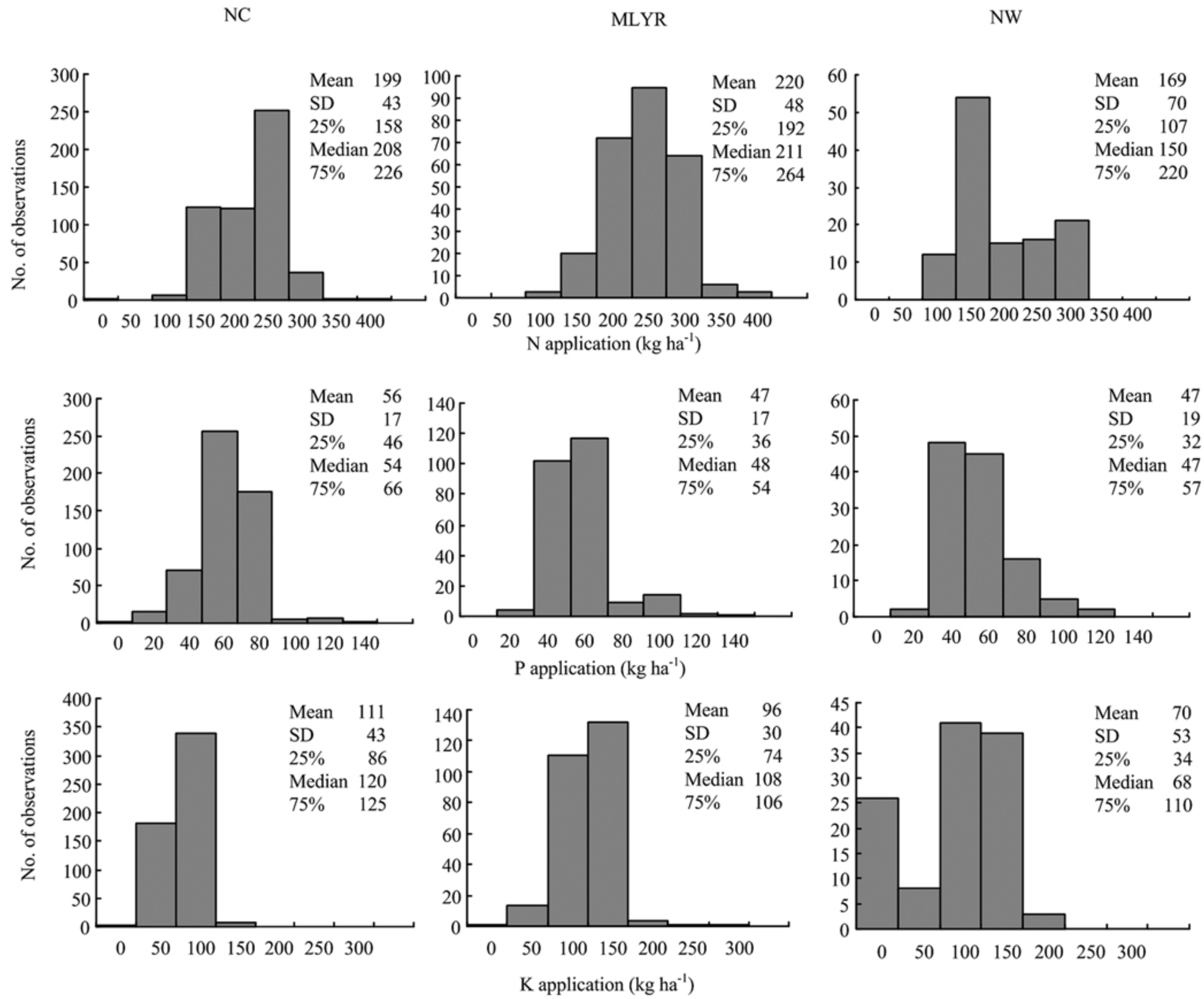

Fig. 3. Frequency distribution of fertilizer application rates in the (OPT) optimal treatment for wheat in north-central (NC) China, the middle and lower reaches of the Yangtze River (MLYR), and northwest (NW) China. The data were calculated based on the OPT treatment in 1022 experiments conducted in China, with 595, 300, 127 experiments in NC China, the MLYR, and NW China, respectively.

increase in N fertilizer inputs by farmers. In NW China, the wheat yield response to P or K fertilization was not significant. Compared with NW China, the wheat yield response to P was higher in NC China but no significant difference in yield response to P was found between the MLYR and NC China. The yield response to K fertilizer was not different among the three regions ($P > 0.05$) (Table 4).

The INS averaged 149.0 kg ha^{-1} in NC China, 91.2 kg ha^{-1} in the MLYR, and 102.8 kg ha^{-1} in NW China (Fig. 5), which indicates that N obtained from both indigenous soil supplies and other environmental sources was the highest in NC China ($P < 0.05$). The IPS averaged 32.2 kg ha^{-1} in NC China, 33.7 kg ha^{-1} in the MLYR, and 18.1 kg ha^{-1} in NW China. The IKS showed spatial variations across the regions ($P < 0.05$) and averaged 129.9 kg ha^{-1} in NC China, 92.0 kg ha^{-1} in the MLYR, and 206.4 kg ha^{-1} in NW China. Trends for IKS coincided with soil K supplying capacity. In the MLYR, because of strong weathering and leaching, the principal clay mineral in the soil is kaolinite, which neither contains nor protects K. Weathering and leaching are relatively weak in NC China, thus the dominant clay minerals are K-bearing hydromicas and K-protecting montmorillonite and vermiculite. In NW China, because of low precipitation and weak weathering and leaching, the dominate clay minerals are K-bearing hydromicas (Xie, 1998, 2002; Huang et al., 1998, 2009). Thus, the K-supplying capability of soils followed the order: NW China > NC China > MLYR. Because of high regional indigenous nutrient supplies, this is an important consideration for nutrient recommendations for wheat in China, especially for N and P in NC China.

The average INS in this study was similar to the average (129 kg ha^{-1}) determined by Cui et al. (2008) in 107 wheat experiments in NC China and the average INS (140 kg ha^{-1}) determined by He et al. (2009) from four sites in Shanxi, Shandong, Henan, and Hebei provinces of NC China. Researchers have always highlighted the INS but often ignore the IPS and IKS. The IPS and IKS obtained from field experiments conducted between 2000 and 2008 in this study were 30.2 and 131.7 kg ha^{-1} respectively, which is lower than the IPS and IKS obtained from field experiments between 1985 and

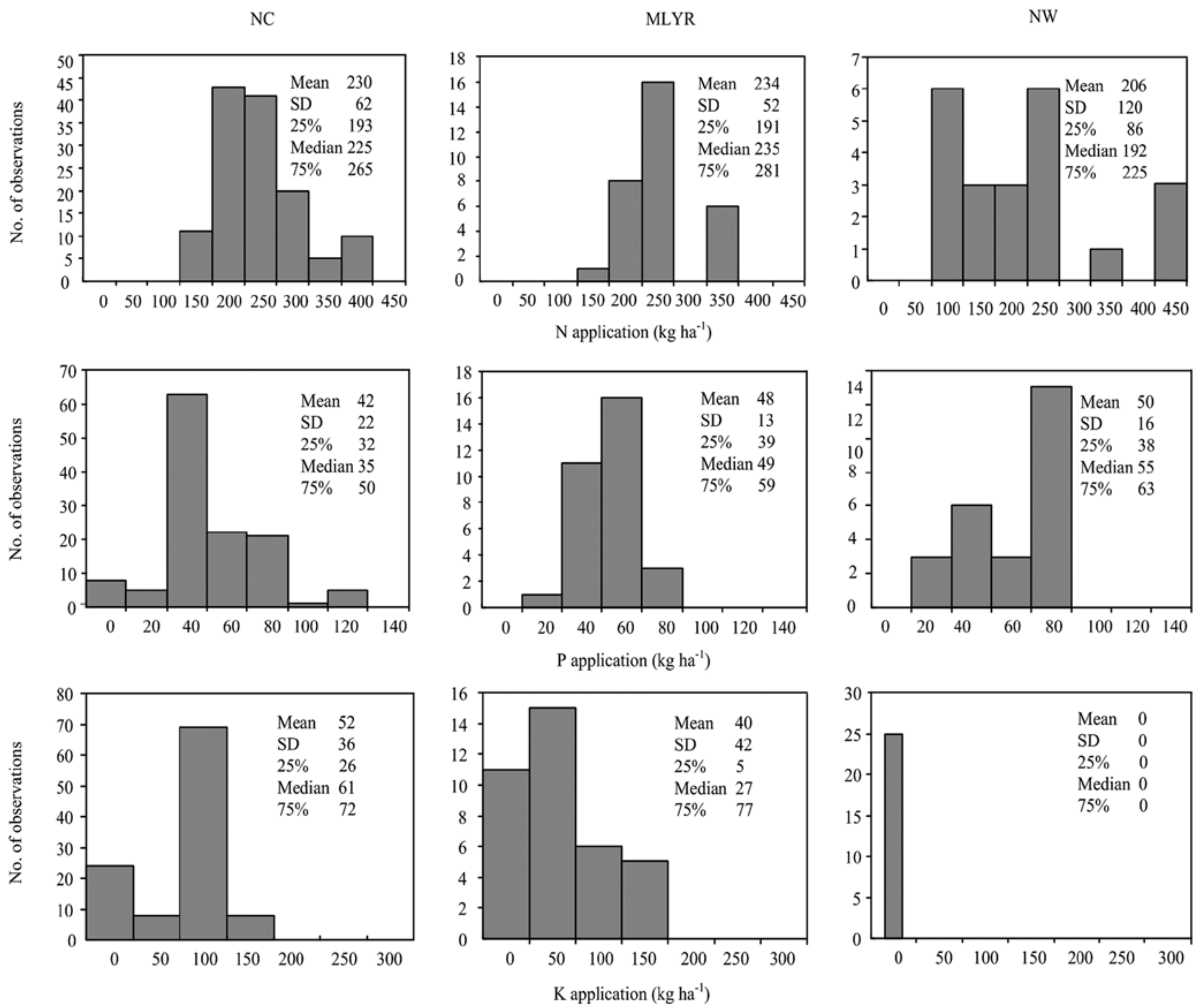

Fig. 4. Frequency distribution of fertilizer application rates in farmers' practice (FP) for wheat in north-central (NC) China, the middle and lower reaches of the Yangtze River (MLYR), and northwest (NW) China. The data were calculated based on the FP treatment in 180 experiments conducted in China, with 123, 32, 25 experiments in NC China, the MLYR, and NW China, respectively.

Table 4. Grain yield response to applied N, P, and K for wheat in different production regions of China.

Region†	N		P		K	
	Yield response	*n*	Yield response	*n*	Yield response	*n*
	Mg ha^{-1}		Mg ha^{-1}		Mg ha^{-1}	
NC China	1.93 (1.63, 2.17)‡	226	1.17 (0.85, 1.51)	138	0.87 (0.72, 1.00)	374
MLYR	2.54 (2.14, 2.94)	92	0.75 (0.39, 1.11)	53	0.71 (0.34,1.08)	69
NW China	1.03 (0.51, 1.53)	35	0.34 (–0.15, 0.83)	40	0.44 (–0.11,0.87)	79
Total (95%CI)	1.84 (1.12, 2.56)	354	0.78 (0.33, 1.24)	231	0.74 (0.51, 0.97)	522
Heterogeneity	$P < 0.0001$		$P = 0.01$		$P = 0.16$	
Test for overall effect	$P < 0.0001$		$P < 0.0001$		$P < 0.0001$	

† NC, north central; MLYR, middle and lower reaches of the Yangtze River; NW, northwest.

‡ 95% confidence interval in parentheses.

1995 reported by Liu et al. (2006). Values for INS, IPS, and IKS under wheat in China were far more than those averages determined for Punjab state in northwest India (66.3, 15.5, and 79.1 kg ha^{-1} for INS, IPS, and IKS, respectively) and in northeast Thailand (38, 10, and 89 kg ha^{-1} for INS, IPS, and IKS, respectively) (Naklang et al., 2006; Khurana et al., 2008). The average INS in China was 133 kg ha^{-1} between 2000 and 2008, a value that is almost 2.5 times that reported by Liu et al. (2006) for a period between 1985 and 1995. The relatively high levels of indigenous N and P supplies probably resulted from excessive nutrient inputs that have contributed to nutrient accumulation in the soil during the past decade. High N and P inputs have increased the residual N and P in the soil and in turn enhanced the INS and INP. Many researchers have also

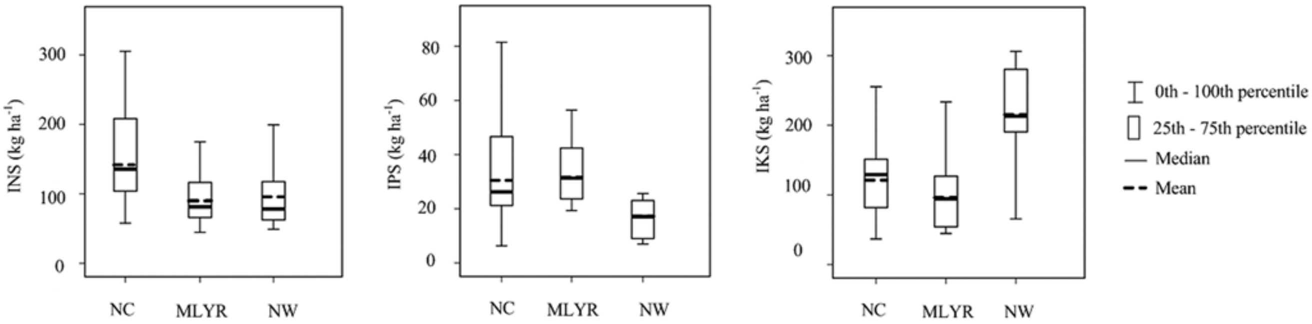

Fig. 5. Variation in the indigenous nutrient supply for wheat in north-central (NC) China, the middle and lower reaches of the Yangtze River (MLYR), and northwest (NW) China; INS, IPS, and IKS indicate indigenous N, P, and K nutrient supply, respectively. The data for INS were calculated based on experiments conducted at 206 sites in China, with 147, 43, and 16 sites in NC China, the MLYR, and NW China, respectively. The data for IPS were calculated based on experiments conducted at 88 sites in China, with 58, 16, and 14 sites in NC China, the MLYR, and NW China, respectively. The data for IKS were calculated based on experiments conducted at 111 sites in China, with 78, 21, and 12 sites in NC China, the MLYR, and NW China, respectively.

indicated that the soil organic content, total N, and available P in China have increased significantly compared with the 1980s (Chen, 2003; Yu et al., 2003; Zhang and Sun, 2006; Wang, 2007; Liu, 2008).

Nutrient Use Efficiencies of Nitrogen, Phosphorus, and Potassium

Internal Efficiency

Internal efficiency is used to evaluate the ability of plants to transform nutrients acquired from all sources (soil and fertilizer) into economic yield (grain). A low IE suggests poor internal nutrient conversion due to stress (i.e., nutrient deficiencies, drought, heat, mineral toxicities, and disease); the IE_N averaged 34.7 kg kg^{-1}, IE_P averaged 206.8 kg kg^{-1}, and IE_K averaged 50.0 kg kg^{-1} in China (Table 5). The IE values for N, P, and K were not significantly different among the three wheat production regions ($P > 0.05$). Compared with the IE values estimated by Liu et al. (2006) from data collected between 1985 and 1995 in China, the average IE_N and IE_P decreased by 14 and 23%, respectively, but the IE_K increased 19% for studies conducted between 2000 and 2008 (Table 5). The values for IE_N and IE_P in this study were lower (27 and 20%, respectively) than those calculated by Pathak et al. (2003) based on experiments conducted at 22 sites in India.

Table 5. Descriptive statistics for the internal efficiency (IE) of applied N, P, and K fertilizer for the optimal nutrient treatment for wheat in different production regions of China

Parameter	Region†	*n*	Mean	SD	Min.	Max.
IE of N, kg kg^{-1}	NC China	200	34.6 a‡	6.2	16.8	48.6
	MLYR	158	34.4 a	5.2	22.2	58.4
	NW China	9	42.5 a	12.6	15.2	60.6
	Avg.	367	34.7	6.0	15.2	60.6
IE of P, kg kg^{-1}	NC China	91	207.7 a	91.8	61.2	627.8
	MLYR	46	193.9 a	31.4	120.5	264.0
	NW China	8	270.8 a	170.8	52.8	492.3
	Avg.	145	206.8	77.0	52.8	627.8
IE of K, kg kg^{-1}	NC China	90	48.4 a	16.7	24.2	93.1
	MLYR	47	55.3 a	28.2	29.4	131.6
	NW China	7	34.8 a	22.0	17.2	69.0
	Avg.	144	50.0	20.7	17.2	131.6

† NC, north central; MLYR, middle and lower reaches of the Yangtze River; NW, northwest.

‡ Means followed by the same letter in a column are not significantly different among different wheat production regions ($P < 0.05$).

Partial Factor Productivity

The average PFP_N of wheat in China was 36.3 kg kg^{-1}. Compared with the PFP_N of wheat in NC and NW China, the PFP_N in the MLYR was relatively low (with an average of 33.3 kg kg^{-1}) (Table 6). The average PFP_P of wheat in China was 142.8 kg kg^{-1}, and no statistically significant difference was found among the three regions. The average PFP_K in China was 71.9 kg kg^{-1}, and no statistically significant difference was found among the three regions. Compared with the PFP values in NC China, higher PFP_P and PFP_K and a lower PFP_N were observed in the MLYR, in accordance with the lower P and K application rates and higher N application rates in the MLYR (Fig. 3).

Partial factor productivity is an appropriate index for comparing the economic benefit of fertilization among different regions. The PFP_N of cereals in developed regions (i.e., North America, Oceania, northeast Asia, western Europe, eastern Europe–central Asia) ranged from 45 to 90 kg kg^{-1}, while globally the PFP_N of cereals averaged 44 kg kg^{-1} during 1999 to 2002–2003 (Dobermann and Cassman, 2005). As a developed country example, in France, the PFP of N, P, and K were 88, 192, and 121 kg kg^{-1}, respectively (FAO, 2004). In this study, balanced fertilization between 2000 and 2008 produced PFP values of 36, 143, and 72 kg kg^{-1} for N, P, and K, respectively; however, the PFP of N, P, and K were only 21, 83, and 172 kg kg^{-1} in farmer's fields (Zhang et al., 2007). There is much room to increase the PFP_N and PFP_P through improved nutrient management. The higher PFP_K in farmers' fields may be the result of underapplication of K fertilizer (Fig. 4). Regardless of management, the current PFP_N and PFP_P values across China were all lower than those of developed countries, such as the United States and some European countries. Differences in the average wheat PFP among regions in the world depend on the attainable yield potential, soil quality, amount and form of nutrient application, and the overall timeliness and quality of other crop management operations. The lower PFP_N and PFP_P in China has been a result of these factors, but large, excessive N and P inputs are probably the major cause. Dobermann

Table 6. Descriptive statistics for partial factor productivity (PFP) and agronomic efficiency (AE) of applied N, P, and K fertilizer in the optimal treatment for wheat in different production regions of China.

Parameter	Region†	*n*	Mean	SD	Min.	Max.
PFP of N, kg kg^{-1}	NC China	518	37.5 a‡	10.0	17.8	110.3
	MLYR	234	33.3 b	20.5	15.1	190.0
	NW China	108	36.9 a	15.5	10.3	79.4
	Avg.	860	36.3	14.4	10.3	190.0
PFP of P, kg kg^{-1}	NC China	506	141.8 a	76.5	46.6	625.6
	MLYR	220	145.7 a	67.7	24.5	343.7
	NW China	108	141.9 a	79.2	38.3	516.2
	Avg.	834	142.8	74.6	24.5	625.6
PFP of K, kg kg^{-1}	NC China	481	71.0 a	36.7	22.6	329.2
	MLYR	234	76.2 a	38.3	29.1	244.6
	NW China	102	66.1 b	39.0	16.5	216.9
	Avg.	817	71.9	37.5	16.5	329.2
AE of N, kg kg^{-1}	NC China	210	9.5 b	6.8	0.0	35.6
	MLYR	90	11.3 a	5.4	1.5	28.6
	NW China	34	6.5 c	5.5	0.0	20.6
	Avg.	334	9.8	6.5	0.0	35.6
AE of P, kg kg^{-1}	NC China	137	23.0 a	18.2	0.0	84.5
	MLYR	51	18.4 a	10.4	1.3	54.0
	NW China	40	7.0 b	7.8	0.0	35.7
	Avg.	223	19.2	16.4	0.0	84.5
AE of K, kg kg^{-1}	NC China	374	7.6 a	5.5	0.0	35.4
	MLYR	69	8.3 a	5.5	0.0	29.6
	NW China	77	4.2 b	5.3	0.0	18.1
	Avg.	517	7.2	5.6	0.0	35.4

† NC, north central; MLYR, middle and lower reaches of the Yangtze River; NW, northwest.

‡ Means followed by different letters for a parameter in a column are significantly different among different wheat production regions ($P < 0.05$).

Table 7. Descriptive statistics for the recovery efficiency (RE) and partial nutrient budget (PNB) of applied N, P, and K fertilizer in optimal treatment (OPT) for wheat in different production regions of China.

Parameter	Region†	*n*	Mean	SD	Min.	Max.
RE of N, %	NC China	122	35.2 b‡	19.0	0.0	83.0
	MLYR	60	48.1 a	13.3	19.6	79.7
	NW China	13	17.0 c	9.4	0.0	24.6
	Avg.	195	37.9	16.6	0.0	83.0
RE of P, %	NC China	46	17.8 b	15.4	0.0	58.0
	MLYR	26	25.9 a	12.8	10.0	68.4
	NW China	11	7.4 c	12.6	0.0	29.5
	Avg.	83	19.0	15.1	0.0	68.4
RE of K, %	NC China	70	23.7 a	18.2	0.0	83.0
	MLYR	26	34.2 a	28.3	0.0	99.0
	NW China	14	30.0 a	27.8	0.0	74.7
	Avg.	110	27.0	21.8	0.0	99.0
PNB of N, kg kg^{-1}	NC China	188	1.10 a	0.33	0.59	2.25
	MLYR	155	0.81 b	0.22	0.45	1.63
	NW China	20	0.70 b	0.30	0.41	1.74
	Avg.	363	0.95	0.28	0.52	1.96
PNB of P, kg kg^{-1}	NC China	89	1.07 a	0.65	0.32	3.28
	MLYR	40	0.91 a	0.52	0.30	2.58
	NW China	19	0.43 b	0.24	0.14	1.14
	Avg.	148	0.96	0.39	0.44	2.30
PNB of K, kg kg^{-1}	NC China	85	1.67 b	1.29	0.32	3.28
	MLYR	46	1.73 b	0.99	0.45	3.80
	NW China	18	2.73 a	1.50	0.24	5.47
	Avg.	149	1.82	1.22	0.35	3.71

† NC, north central; MLYR, middle and lower reaches of the Yangtze River; NW, northwest.

‡ Means followed by different letters for a parameter in a column are significantly different among different wheat production regions ($P < 0.05$).

and Cassman (2005) reported that the global PFP_N in cereals needs to increase at a rate of 0.1 to 0.4% yr^{-1} to meet the cereal demand in 2025 at a modest pace of increased N consumption. In China, however, a declining trend in the average PFP_N in wheat was found between 1981 to 1983 (Institute of Soil and Fertilizer, Chinese Academy of Agricultural Sciences, 1986) and 2000 to 2008.

Agronomic Efficiency

The AE_N averaged 9.8 kg kg^{-1}, AE_P averaged 19.2 kg kg^{-1} and AE_K averaged 7.2 kg kg^{-1} across the three regions in China (Table 6). The AE values of N, P, and K for spring wheat in NW China were all lower than for winter wheat in NC China and the MLYR ($P < 0.05$). In most cases, the trends for AE were in accordance with the N, P, and K responses in Table 4. Dobermann (2007) reported that the AE_N in cereals varied between 10 and 30 kg kg^{-1} and could reach >30 kg kg^{-1} in well-managed systems with low levels of N or with a low soil N supply. The average AE_N in China only reached the baseline reported by Dobermann (2007) and the value was only 54% of the world average (18 kg kg^{-1}) reported by Ladha et al. (2005).

Nutrient Recovery Efficiencies

The mean RE values of applied N, P, and K fertilizers observed in the OPT experiments were 37.9, 19.0, and 27.0%, respectively, in China (Table 7). Great variation was observed for RE, ranging from 0 to 83.0, 0 to 68.4, and 0 to 99.0% for RE_N, RE_P, and RE_K, respectively. Fertilizer nutrients applied but not taken up by the crop are vulnerable to losses from leaching, erosion, and, in the case of N, denitrification or volatilization, all of which impact NUE. The RE was 35.2, 48.1, and 17.0% for N, 17.8, 25.9, and 7.4% for P, and 23.7, 34.2, and 30.0% for K in NC China, the MLYR, and NW China, respectively. The RE_N and RE_P values in NC China were lower than in the MLYR and higher than in NW China ($P < 0.05$), but RE_K showed no significant difference across the three regions (Table 7).

The RE_N in this study was similar to data (36%) from plots with optimum N, P, and K combination fertilization in 87 field experiments during 2000 and 2005 (Zhang et al., 2008). Compared with RE measured between 1985 and 1995, however, these current RE values are 7.1, 3.0, and 20.0% lower for N, P, and K, respectively (Liu et al., 2006). A review of worldwide data on use efficiency for cereal crops from researcher-managed experimental plots reported that the single-year fertilizer RE_N averaged 57% for wheat (Ladha et al., 2005). Most of the data reported by Ladha et al. (2005) were based on multiyear or long-term trials with stationary treatment plots, but that report also indicated that the RE_N of wheat in China was far less than the world's average, especially when compared with the United States and some European countries (Ladha et al., 2005;

Pathak et al., 2003; Dobermann, 2007). The RE_N mainly depends on the degree of synchrony between N supply and demand [expressed as applied fertilizer N/(1 – INS/N uptake)] (Cassman et al., 2002), so the lower REs in China were a result of the interactive effects of indigenous nutrient supply, fertilizer application, and wheat nutrient uptake for a target yield.

Partial Nutrient Budgets

The PNBs of N, P, and K averaged 0.95, 0.96, and 1.82 kg kg^{-1}, respectively (Table 7). Wheat in NC China had higher PNB_N and PNB_P values than NW China ($P < 0.05$). The PNB_N in NC China was significantly lower than that in the MLYR, while there was no significant difference in PNB_P between the two regions. The PNB_K showed no significant difference across the three regions. Nitrogen and P application rates, even in OPT treatments, were in surplus to various extents within the MLYR and NW China, and N and P application rates were relatively rational in NC China.

In these experimental plots, no straw was returned to the field. The current values of PNBs were calculated under the assumption of complete nutrient removal in harvested grain and straw. By estimation, an average of 44% of the wheat straw nutrient resource is returned to the field in China (Gao et al., 2009), so the PNBs in this study were overestimated. If all straw was returned to the field, the PNB_N, PNB_P, and PNB_K would be 0.73, 0.81, and 0.60 kg kg^{-1}, respectively (data not shown). Therefore, it was inferred that PNBs ranged from 0.73 to 0.95 kg kg^{-1} for N, 0.81 to 0.96 kg kg^{-1} for P, and 0.60 to 1.82 kg kg^{-1} for K given the current amount of wheat straw recycling. It could be concluded that N and P in the current wheat systems were all in surplus at the national scale regardless of straw recycling. This surplus of N and P nutrients can again be related to the observed increase in indigenous nutrient supply and, in turn, the decreased RE and AE of N and P.

Fertilizer use efficiency is affected by several factors such as soil properties, the amount and species of the fertilizer used, efficiency of cultivars, climate, and others (Baligar et al., 2001). Excluding soil fertility and fertilizer application rates, climatic factors such as temperature, precipitation, and solar radiation during crop growth have a large influence on nutrient availability in the soil and the plant's ability to take up and utilize nutrients and transform them into grain yield. Some NUE indices (AEs, REs, and PNBs) for spring wheat in NW China were lower than those for winter wheat in the MLYR (Tables 6 and 7), which may be partially due to relatively low temperature and precipitation in NW China (Table 1; Fig. 1).

These NUE data were obtained from experimental plots under balanced fertilization, so the actual NUE in many farmers' fields are probably much lower (Zhang et al., 2008; He et al., 2009). Satisfying the growing demand for food and pursuing high yield is the primary goal for governments and researchers during the past few decades, and increasing amounts of mineral fertilizers were applied to reach this goal. When fertilizer is applied at rates greater than is required for maximum yield, however, N and P surpluses are created in the wheat cropping systems (Table 7) and the NUE falls. Even under balanced fertilizer management, the current NUE for wheat in China is lower than in developed countries, such as the United States and some European countries. Investments in crop improvement (high-yielding cultivars with stress tolerance), new fertilizer products, application technology algorithms and support services for better fertilizer recommendations, better soil and crop management technologies, extension education, and local regulation of excessive N use by both the public and the private sector have contributed to better N use efficiency (Cassman et al., 2002; Dobermann, 2007). Many of the recently developed approaches and decision support tools for fine-tuned N management increase the NUE by deceasing N fertilizer rates, but substantial and consistent yield increases have been demonstrated in only a few studies (Zhang et al., 2007; Dobermann and Cassman, 2005). Therefore, more quantitative approaches to characterizing nutrient needs in relation to seasonal and site-specific yield potential will be needed, especially for China.

SUMMARY AND CONCLUSIONS

Compared to the OPT, the FP treatments overapplied N and underapplied K. High N input has contributed to increased INS, and in turn decreased many indices of NUE. It should be noted that some OPT treatments in this study focused only on better nutrient management and ignored other high-yield cultivation techniques (high-yielding cultivars with stress tolerance, optimum sowing date, optimum water content, etc.), so Y_a, yield gaps, and yield response to nutrients may all be underestimated. The YG_f of 12% might be narrowed if farmers improved their fertilizer management (i.e., the right balance of nutrients, the right fertilizer form, the right placement, and the right timing based on soil testing and target yields), which would be beneficial agronomically, economically, and environmentally. Many researchers have demonstrated experimentally that additions of N fertilizer could be cut by 20 to 50% without loss of yield, with the OPT treatment being either similar to or more cost effective than the FP treatment (He et al., 2009; Ju et al., 2009). We can infer that closing the current YG_f for wheat would be sufficient to satisfy demand for the next 10 yr, but it would not be sufficient to meet the need of a Chinese population expected to reach 1.6 billion within 40 yr. Increasing the potential yield or the attainable yield under experimental conditions will be a pivotal component of China's food security. In China, more management practices should be studied and adopted, including balanced fertilization, split application of N fertilizer, advanced technologies for the diagnosis of soils and plants, breeding cultivars with high nutrient uptake efficiency and utilization and strong resistance to stress, high-yielding cultivation systems, and others (Cassman et al., 2003; Witt et al., 2005; Hirel et al., 2007; Anderson, 2008).

Our research only clarified the extent to which the YG_f can be closed, and there is still a long way to go to narrow the yield gaps, improve nutrient efficiency, and diminish nutrient losses to the environment. Simple balanced fertilizer management (including macro-, secondary, and micronutrients) has not received enough attention by many farmers in China. Many farmers equate more N application to more yield, and many farmers in China obtain more knowledge and experience from their neighbor than from research-based educational programs. A recent survey showed that, in developed regions of China, only 11 to 17% of the farmers applied high fertilizer rates based on soil testing, and the results are even lower in less developed regions (Magen et al., 2007). Scientific success in research plots does not guarantee the adoption of a new technology and does not guarantee yield increases in farmers' fields. Therefore, agricultural extension programs on science and technology must be strengthened. Improving education and the technological training of farmers will make an important contribution to meeting China's demands for wheat.

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