A Long-term Analysis of Factors to Improve Nutrient Management for Winter Wheat Production in China

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Data from 895 field experiments conducted between 2000 and 2008 were analyzed to calculate yield gaps, indigenous nutrient supplies, and nutrient use efficiencies – with the goal of improving nutrient management for wheat. Results showed an average yield gap of 0.76 t/ha between attainable yields and yields with farmers' practice. Successive inputs of large amounts of nutrients have significantly increased soil nutrient supply, and therefore contribute to lower use efficiencies since recommendations for N, P, and K have not been adjusted downward.

In the last three decades, an increase in nutrient inputs has played a major role in increasing food supplies in China. However, crop yields have not increased at the same rate as fertilizer application. Over application of N fertilizer is a common problem in wheat-maize and wheat-rice rotation systems. In the case of N, it has led to nutrient imbalances, inefficient use, and large losses to the environment – impacting air and water quality, biodiversity, and human health. Nutrient management within this system must be improved, and essential precursors to improving nutrient management in wheat include an assessment of wheat yield gaps, indigenous nutrient supplies, and nutrient use efficiency (NUE).

Inefficient crop management may cause actual yield to deviate from potential yields – this difference is termed the "yield gap" (Tittonell et al., 2008; Neumann et al., 2010). Field experimentation provides a direct measure of 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. Indigenous nutrient supply can be defined as the cumulative quantity of nutrients from all non-fertilizer sources that are found in the soil solution surrounding the root system (Dobermann et al., 2003). NUE is an important index not only for fertilizer recommendations on a field-scale, but also for forecasting fertilizer demand on regional- and national-scales. Partial factor productivity (PFP), agronomic efficiency (AE), recovery efficiency (RE), and partial nutrient budgets (PNB) of applied nutrients are frequently used in agronomic research to assess NUE (Dobermann, 2007; Snyder and Bruulsema, 2007).

China, with the world's largest wheat sowing area of 24 million ha, produced 115 million t of wheat grain in 2009. Winter wheat is mainly planted in North central (NC) China and the middle and lower reaches of the Yangtze River (MLYR) **(Figure 1)**. This area accounts for more than 90% of China's total wheat production. NC China is dominated by a temperate climate and a winter wheat/maize annual rotation. The MLYR has a temperate to subtropical humid climate and predominant rice/wheat rotation system.

Data were obtained from field experiments conducted by the IPNI China Program and other published studies between 2000 and 2008 **(Figure 1)**. Treatments consisted of optimum nutrient treatments (OPT) based on soil testing and target yields (He et al., 2009), a series of nutrient omission treatments consisting of an OPT-N, OPT-P, OPT-K, a check without any fertilizer applied (CK), and farmers practice (FP). The average rates of applied nutrient in these OPT treatments are shown in **Table 1**. Plot size ranged from 20 to 50 m^2 depending on location. These experiments covered a wide range of soils, crop varieties, agronomic practices, cropping systems, and climatic conditions.

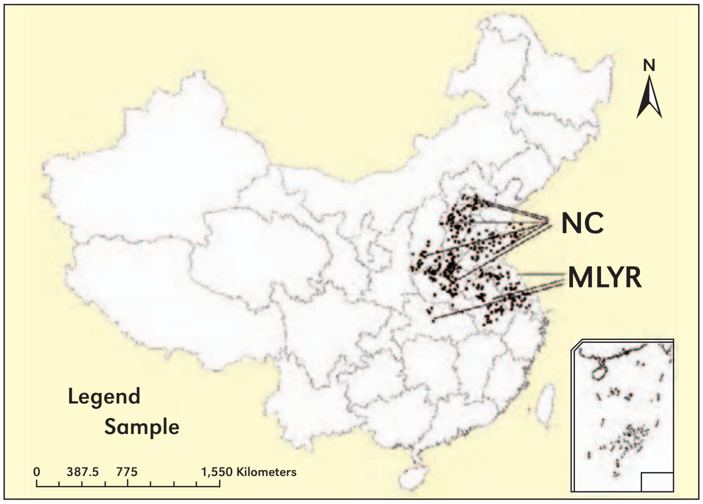

Figure 1. Geographical distribution of studied locations in different wheat production regions in China.

Table 1. Fertilizer application rates (kg/ha) in OPT and FP treatments.

	OPT				FP			
Regions	N	P	K	n[1]	N	P	K	n
NC	199	56	111	595	230	42	52	123
MLYR	220	47	96	300	234	48	40	32

[1] n = number of observations.

Abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium; Y_a = attainable yield; Y_{ck} = yield without nutrient applied; Y_f = yield with farmer's practice.

Yield Gaps

In this study, we define yield potential as Y_a given best nutrient management practices under experimental conditions. Y_a, Y_f, and Y_{ck} define yields obtained from OPT, FP, and CK treatments, respectively. The farmer-based yield gap (YG_f) is the yield difference between Y_a and Y_f. The check-based yield gap (YG_{ck}) is the yield difference between Y_a and Y_{ck}.

YG_f in NC China and the MLYR were 0.79 and 0.69 t/ha, and were 11% and 10% of Y_a, respectively **(Figure 2)** – values similar to those calculated by Neumann et al. (2010).

Y_{ck} is usually used as the indicator of soil fertility. Y_{ck} obtained in NC China and the MLYR averaged 4.52 and 2.79 t/ha, respectively, indicating that basic soil fertility was higher in NC China compared to the MLYR. YG_{ck} was 2.65

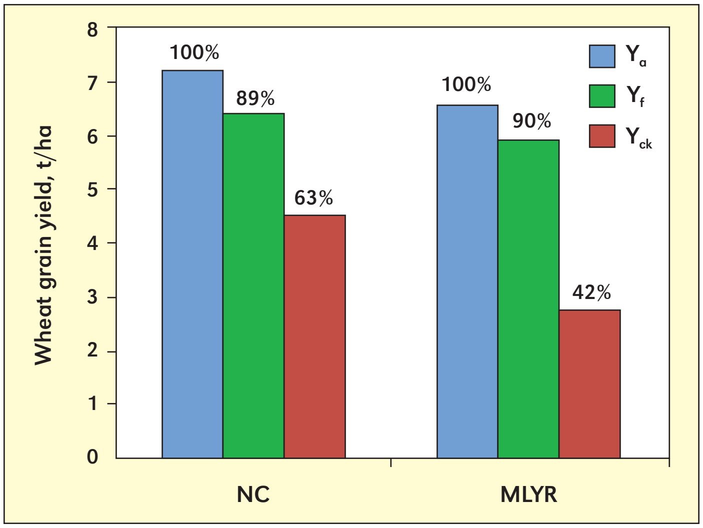

Figure 2. Differences Y_a, Y_f, and Y_{ck} in experimental plots for winter wheat in NC China and MLYR, respectively.

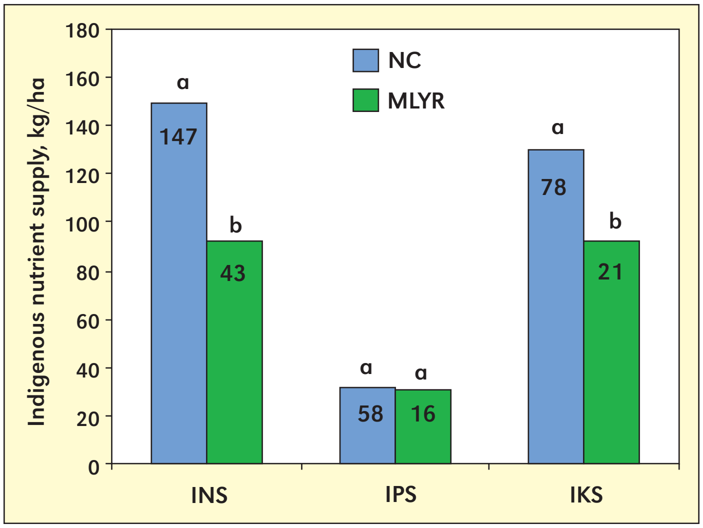

Figure 3. Variation in the indigenous nutrient supply in wheat fields in NC China and the MLYR. Numbers within each bar in the graph indicate the numbers of experiments with omission plots in each region. Different letters above the columns indicate a significant difference at $p < 0.05$.

and 3.77 t/ha in NC China and the MLYR, respectively. Data indicated that 37% and 58% of winter wheat yield was due to chemical fertilizer application in NC China and the MLYR, respectively. Thus fertilizer omission had its largest impact on yield in MLYR.

Indigenous Nutrient Supply

Indigenous nutrient supply refers to the contribution from all soil and environmental sources. The indigenous supplies of N (INS), P (INP), and K (INK) were estimated from total plant nutrient accumulation at maturity in 0-N plots, 0-P plots, and 0-K plots, respectively. Large differences were observed in INS and IKS supplies between the NC China and MYLR regions (58 and 38 kg/ha, respectively) **(Figure 3)**. However, this regional difference was non-significant for IPS.

The average INS in NC China was similar to the values determined in some recent studies (Cui et al., 2008; He et al., 2009). Interestingly, however, these values were almost 2.4 times that reported by Liu et al. (2006) for a study period between 1985 and 1995. Similarly, the IPS and IKS values in the present study were also higher than those obtained by Liu et al. (2006). In addition, INS, IPS, and IKS values for winter wheat in China were far more than those determined for Punjab state in northwest India (Khurana et al., 2008) and for northeast Thailand (Nakland et al., 2006). These relatively high levels of indigenous nutrient supplies are likely a result of large nutrient input, which has contributed to nutrient accumulation over the past decade, and should be an important consideration in formulating efficient nutrient management recommendations for winter wheat in China.

Nutrient Use Efficiencies of N, P, and K

Nutrient use efficiency parameters included PFP, AE, RE, and PNB from OPT plots. PFP, calculated as units of crop yield per unit of nutrient applied, is an appropriate index for comparing the economic benefit of fertilization among different regions. The average PFP$_N$ of winter wheat in China was 36.2 kg/kg **(Table 2)**. Compared with PFP$_N$ of wheat in NC China, the PFP$_N$ in the MLYR was relatively low (33.3 kg/kg). In these two regions, average PFP$_P$ was 143 kg/kg while average PFP$_K$ was 72.7 kg/kg. No statistically significant differences for PFP$_P$ and PFP$_K$ were found within the two regions studied.

Average results for AE$_N$, AE$_P$, and AE$_K$ were 10.0, 21.8, and 7.7 kg/kg, respectively, for winter wheat in China. Dobermann (2007) reported that AE$_N$ in cereals varied between 10 to 30 kg/kg and could reach >30 kg/kg, in well-managed systems, with low levels of N, or with low soil N supply. The average AE$_N$ in China only reached the baseline reported by Dobermann (2007) and the value was only 55% of the world average (18 kg/kg) reported by Ladha et al., (2005). The AE$_N$ in the MLYR was higher than in NC China. However, there was no significant difference for AE$_P$ and AE$_K$ between the MLYR and NC China.

RE is defined as the increase in crop uptake of a nutrient in above-ground parts of the plant in response to application of that nutrient. Mean RE of applied N, P, and K fertilizer observed in OPT experiments were 39.5%, 20.7%, and 26.5% for winter wheat in China, respectively **(Table 2)**. RE$_N$ and RE$_P$ in NC China were lower than that in the MLYR. But RE$_K$ showed no significant difference across the two regions. Compared to RE measured between 1985 and 1995, these current RE values are 5.5, 1.3, and 20.5% 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 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 multi-year or long-term trials with stationary treatment plots, but that also indicated that the RE$_N$ of wheat in China was far less than the world's average, especially when compared against the United States, and some European countries (Pathak et al., 2003; Ladha et al., 2005; Dobermann, 2007).

PNB is used to evaluate the sustainability of a cropping system and is calculated in units of nutrient uptake by harvested portion per unit of kg nutrient applied. PNB is >1 in nutrient deficient systems (fertility improvement), <1 in nutrient surplus systems (under-replacement) and slightly less than 1:1 in sustainable systems (Snyder and Bruulsema, 2007). The PNB of N, P, and K averaged 0.95, 0.96, and 1.82 kg/kg, respectively **(Table 2)**. PNB$_N$ in NC China was significantly

Table 2. Nutrient use efficiency of applied N, P, and K fertilizer in OPT treatments for winter wheat production regions of China.

	PFP		AE		RE		PNB	
Regions	kg/kg	n[1]	kg/kg	n	%	n	kg/kg	n
				N use efficiency				
NC	37.5 a[2]	518	9.5 b	210	35.2 b	122	1.10 a	188
MLYR	33.3 b	234	11.3 a	90	48.1 a	60	0.81 b	155
Average	36.2	752	10.0	300	39.5	182	0.97	343
				P use efficiency				
NC	141.8 a	506	23.0 a	137	17.8 b	46	1.07 a	89
MLYR	145.7 a	220	18.4 a	51	25.9 a	26	0.91 a	40
Average	143.0	726	21.8	188	20.7	72	1.02	129
				K use efficiency				
NC	71.0 a	481	7.6 a	374	23.7 a	70	1.67 b	85
MLYR	76.2 a	234	8.3 a	69	34.2 a	26	1.73 b	46
Average	72.7	715	7.7	443	26.5	96	1.69	131

[1] n = number of observations.

[2] Means within a column followed by different letters are significantly different ($p<0.05$).

higher than that in the MLYR, while there was no significant difference in PNB$_P$ between the two regions. This surplus of N and P nutrients can again be related to the observed increase in indigenous nutrient supply, and in turn, decreased RE and AE of N and P. PNB$_K$ showed no significant difference between the two regions. PNB$_K$ is >1 in the two regions, indicating that K application rates were not replacing K removal.

Conclusion

Compared to the OPT, the FP treatments over applied N and under applied 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 only focused on better nutrient management and ignored other high-yield cultivation techniques (i.e. high yielding varieties with stress tolerance, optimum sowing date, optimum water content, etc.) so yield gaps may be under estimated. The YG$_f$ of 10 to 11% could be narrowed through improved fertilizer management (i.e. adopting 4R nutrient stewardship that focuses on providing the right nutrient source at the right rate, time, and place based on soil testing and target yields), which would provide agronomic, economic, and environment benefits.

Our research only clarified the extent that YG$_f$ can be closed, but there is still a long way to narrow the yield gaps, improve nutrient efficiency, and diminish nutrient loss to the environment. Simple balanced fertilizer management (including macro-, secondary, and micronutrients) has not been given 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 rather than from research-based educational programs. A recent survey showed that, in developed regions of China, only 11 to 17% of farmers applied fertilizer rates that are 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 farmer's fields. Improving education and the technological training of farmers will make an important contribution to meeting China's demands for wheat.

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