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Estimating nutrient uptake requirements for wheat in China

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ABSTRACT

Estimating balanced nutrient requirement for wheat (*Triticum aestivum* L.) in China is essential to manage nutrient application more effectively for increasing crop yields and reducing risk of negative environmental impact. Datasets from 2000 to 2011 dealing with nitrogen (N), phosphorus (P) and potassium (K) treatments across the winter and spring wheat growing regions in China were collected to assess the relationship between grain yield and nutrient uptake, and to estimate N, P and K optimal nutrient requirements for a target yield using the QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils) model. In the QUEFTS model, two boundary lines described the minimum and maximum internal efficiencies (IEs, kg grain per kg nutrient in above-ground plant dry matter) of N, P and K. The minimum and maximum IEs for wheat were 28.8 and 62.6 kg grain per kg N, 98.9 and 487.4 kg grain per kg P, and 23.0 and 112.9 kg grain per kg K. The QUEFTS model predicted a linear–parabolic–plateau curve for balanced nutrient uptake with target yield increasing. The linear part continued until the yield was approximately at 60–70% of the potential yield, and 22.8 kg N, 4.4 kg P and 19.0 kg K were required to produce 1000 kg grain. The corresponding N:P:K ratio was 5.18:1:4.32, and the corresponding IEs were 43.9, 227.0 and 52.7 kg grain per kg N, P and K, respectively. The QUEFTS model simulated balanced N, P and K removal by 1000 kg grain were 18.3, 3.6 and 3.5 kg, respectively, with a N:P:K ratio of 5.08:1:0.97. Approximately 80%, 82% and 18% of N, P and K in total above-ground plant material were presented in the grain and removed from the field. The relationship between grain yield and nutrient uptake was also estimated to suggest fertilizer application avoiding excess or deficient nutrient supply. Field experiment validation confirmed that the QUEFTS model could be used as a practical tool for the *Nutrient Expert* decision support system to make fertilizer recommendation.

1. Introduction

Wheat (*Triticum aestivum* L.) is an important cereal crop in China, and it is usually grown in rotation with maize (*Zea mays* L.) in North Central China, with rice (*Oryza sativa* L.) in the middle and lower reaches of the Yangtze River, and winter and spring wheat are both grown in Northwest China. The yield has been improved in the last decade, but the total production has been stagnant and even decrease due to the planting area changing. Fertilizer application has played a dominant role in increasing yield; however, current fertilizer management approaches do not usually apply in balance to match crop demand, resulting in waste of fertilizer resources and low nutrient use efficiency (Zhang et al., 2009). To improve the efficiency of fertilizer inputs, a computer software program named *Nutrient Expert* (NE) is a new decision support system to make fertilizer recommendation. This NE system is based on improved site-specific nutrient management (SSNM) and the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model to guide fertilizer application, with integrated consideration of balanced inputs of all plant nutrients (He et al., 2012; Pampolino et al., 2011, Pampolino et al., 2012; Satyanarayana et al., 2011).

SSNM could closely match nutrient supply and demand within a specific field for splitting and timing of fertilizer application, as well as use of the chlorophyll meter or leaf color chart as an indicator to change crop nitrogen (N) demand in a particular season (Dobermann et al., 2004). Strategies for SSNM that assess crop

Abbreviations: HI, harvest index; IE, internal efficiency; K, potassium; N, nitrogen; NE, nutrient expert; OPT, optimal practice treatment; P, phosphorus; RE, recovery efficiency; RIE, reciprocal internal efficiency; SSNM, site-specific nutrient management.

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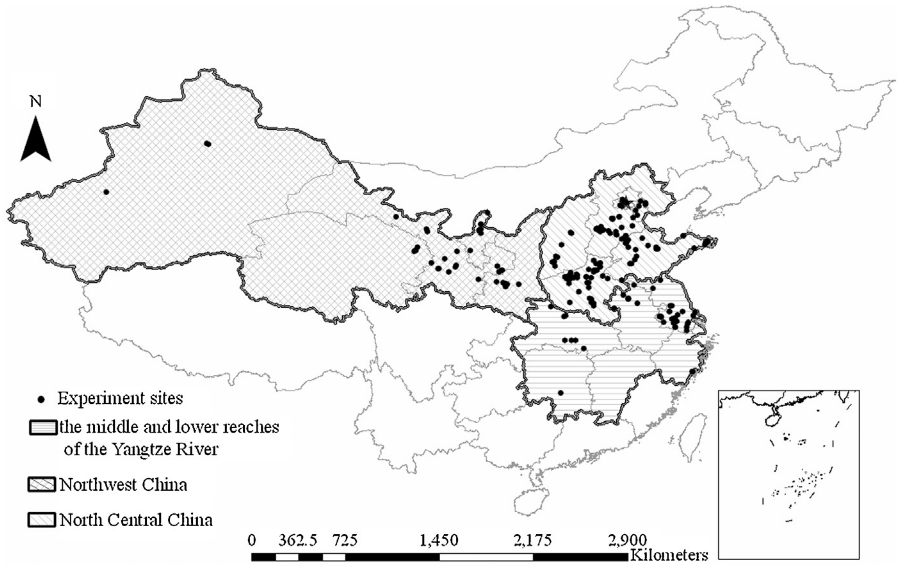

Fig. 1. Geographical distribution of studied locations in North Central China, the middle and lower reaches of the Yangtze River, and Northwest China. The black solid lines are the boundaries of each region.

nutrient requirements, indigenous nutrient supply and recovery efficiency (RE, the fraction of nutrient uptake in above-ground biomass to the nutrient applied) of applied fertilizer could be used to increase crop yield and nutrient use efficiency. These principles to determine field- and season-specific fertilizer application have been applied successfully on rice (Buresh and Witt, 2007; Witt et al., 2007; Buresh, 2009), wheat (Khurana et al., 2008) and maize (Witt et al., 2009).

However, there were many uncertainties about N, phosphorus (P) and potassium (K) nutrient requirements of crops because the internal efficiency (IE, the amount of grain yield produced per unit of nutrient accumulated in above-ground plant dry matter) varied greatly depending on the very broad ranges of soil, nutrient supply, crop management and climate conditions encountered, making it difficult to extrapolate to small farmers' field (Van Duivenbooden et al., 1996). Therefore, the SSNM approach advocated that more generic and quantitative approaches such as some simulation models should be established to estimate the relationships between grain yield and nutrient uptake to help make fertilizer recommendations (Witt et al., 1999; Maiti et al., 2006).

The QUEFTS model then was selected to resolve this problem, since it took into account the interactions of N, P and K, which was the most important and different characteristic from other models (Janssen et al., 1990). The QUEFTS model provided a generic empirical relationship between grain yield and nutrient accumulation in plants following a linear-parabolic-plateau model, also used two linear boundaries to describe the range between maximum nutrient accumulation (a) and maximum nutrient dilution (d) situations (Smaling and Janssen, 1993; Witt et al., 1999; Witt and Dobermann, 2004). The QUEFTS model has been applied on rice in Asia, India and West Africa (Witt et al., 1999; Haefele et al., 2003; Das et al., 2009; Buresh et al., 2010), wheat in India and China (Pathak et al., 2003; Liu et al., 2006), and maize in Africa, Nigeria, Kenya, Nebraska, Southeast Asia and China (Janssen et al., 1990; Saidou et al., 2003; Liu et al., 2006; Tabi et al., 2008; Tittonell et al., 2008; Setiyono et al., 2010). It provided a very practical tool for site-specific nutrient management concepts for major crops (Dobermann et al., 2002; Khurana et al., 2008; Witt et al., 2008; Setiyono et al., 2010).

A previous study of the QUEFTS model on wheat in China was published in 2006 (Liu et al., 2006), and used a smaller region mainly in Huang-huai-hai plain and a smaller dataset only from 1985 to 1995, with yield potential set at 10,000 kg/ha for wheat. However, in this study, datasets were different from Liu's that covered a wide range of wheat yield, soil types and climate, including more recent data from the year 2000 to 2011. The soil types and climate covered North Central China, the middle and lower reaches of the Yangtze River and Northwest China. The crop varieties, fertilizer utilization and environmental adaptability were very different from those in 1985–1995, which were the most important influencing factors on nutrient uptake. These datasets allowed the estimation of new relationships between grain yield and nutrient uptake, also as a support to the background database of NE for wheat as we mentioned above. Therefore, the objective of this study was to estimate the optimal nutrient requirements of N, P and K uptake for a specific target yield using the QUEFTS model.

2. Materials and methods

2.1. Data source

Datasets for grain yield, N, P and K uptake in above-ground plant dry matter, harvest index (HI, kg grain per kg total above-ground dry matter) and fertilizer application were compiled from published literature from the year 2000 to 2011 in China, and published or unpublished datasets from the International Plant Nutrition Institute (IPNI) China Program database. The datasets contained many different nutrient management practices to establish a wide range of nutrient dilution and accumulation situations, including farmers' practice, optimal practice treatment (OPT), long-term field experiments and different rates of fertilizer treatments across wheat-growing environments of China, encompassing North Central China, the middle and lower reaches of the Yangtze River and Northwest China (Fig. 1). The data included a wide range of soil types and climate conditions, with a large variation in soil properties (Tables 1 and 2). The wheat varieties in the experiments were all commonly used in local high yield production and highly represent the great variation in the wheat production area.

2.2. Model background

The QUEFTS was originally developed by Janssen et al. (1990), affirmed that the yield was a combined function of N, P and K, and described the relationship between grain yield and nutrient uptake following four steps: (1) assess the potential indigenous

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

Region	Province	season	n[a]	Precipitation (mm)	Latitude	Longitude	T_{min}[b]	T_{max}[c]
NC[d]	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[e]	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[f]	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

[a] n = number of the observations.
[b] T_{min} = minimum temperature.
[c] T_{max} = maximum temperature.
[d] NC = North Central China.
[e] MLYR = the middle and lower reaches of the Yangtze River.
[f] NW = Northwest China.

nutrient supply based on the soil chemical character; (2) calculate the actual uptakes of N, P and K based on the potential supplies of N, P and K. Nutrients are compared in pairs, for an example, the relationship between the actual uptake and the potential supply of N is calculated twice: one is depending on the potential supply of P, and another is depending on the potential supply of K. Likewise, the actual P uptake is depending on the potential supply of N and the potential supply of K, and the actual K uptake is depending on the potential supply of N and the potential supply of P; (3) identify the yield ranges as functions of the actual uptakes of N,

Table 2
Soil properties of experimental sites for wheat production in three regions of China.

Region	Province	Main Soil type	pH	Organic matter (g/kg)	Alkali- hydrolysable N (mg/kg)	Olsen P (mg/kg)	NH_4OAc-K (mg/kg)
NC[a]	Hebei	Haplic Luvisol; Eutric Fluvisol; Dystric Fluvisol; Eutyic Cambisol	7.8–8.6	8.0–19.3	45.2–99.8	3.6–53.2	67.9–157.5
	Henan	Haplic Luvisol; Eutric Fluvisol; Calcic Vertisol; Dystric Fluvisol	6.1–8.4	4.0–20.5	43.6–113.0	3.1–67.5	54.1–152.5
	Shanxi	Haplic Luvisol; Dystric Fluvisol	7.4–8.2	11.2–18.0	46.4–88.1	13.1–16.5	95.0–201.5
	Shandong	Haplic Luvisol; Eutric Fluvisol; Gleyic Cambisol	5.5–8.5	6.8–18.9	37.5–114.7	8.4–70.2	53.0–187.8
	Beijing	Eutric Fluvisol; Dystric Fluvisol	7.8–8.5	6.1–26.7	49.7–78.0	12.0–41.9	87.7–99.5
MLYR[b]	Jiangsu	Haplic Luvisol; Hydragric Anthrosol; Eutric Fluvisol; Umbric Gleysol; Calcic Vertisol	7.3–8.2	9.2–35.0	42.3–198.8	2.45–107.9	42.4–180.8
	Hubei	Haplic Luvisol; Hydragric Anthrosol	6.6–7.3	11.0–12.3	78.8–83.7	16.2–33.3	51.1–152.0
	Anhui	Haplic Luvisol; Hydragric Anthrosol; Eutric Vertisol	5.3–8.3	11.9–18.2	50.4–103.5	13.0–38.5	111.6–270.1
	Hunan	Haplic Acrisol	4.9–5.7	5.4–8.9	50.4–79.3	4.7–10.8	104.2–122.6
NW[c]	Shaanxi	Cumulic Anthrosol; Cumuli-Haplic Kastanozem	7.4–8.6	5.7–17.1	35.5–115.4	2.2–61.4	93.0–191.0
	Ningxia	Calcaric Fluvisal; Eutric Fluvisol	7.5–8.1	10.7–15.9	50.8–70.4	9.9–31.8	144.2–226.7
	Gansu	Haplic Podzol; Gelic Histosol	7.7–8.8	12.9–19.3	48.2–234.2	16.3–37.6	130.3–233.8
	Xinjiang	Luvic Gypsisol; Calcaric Cambisol	7.6–8.1	6.4–8.9	55.2–80.4	3.9–5.7	220.4–288.5

[a] NC = North Central China.
[b] MLYR = the middle and lower reaches of the Yangtze River.
[c] NW = Northwest China.

Table 3
Rates of fertilizer application in optimal practice treatment (OPT).

Province	Fertilizer application (kg/ha)		
	N	P	K
Hebei	135(130–150)[a]	23(22–24)	50(40–58)
Henan	150(140–170)	32(29–34)	62(50–66)
Shandong	140	34	58(50–66)
Shanxi	137(125–140)	29	65(50–66)

[a] Data in parentheses indicates the range of fertilizer application.

P and K determined in Step 2 at the situations of maximum accumulation (where the nutrient is sufficient supply) and maximum dilution (where the nutrient is deficient supply); (4) estimate the actual yield based on the three yield ranges (one range each for N, P and K) identified under Step 3 and anticipated interactions between N, P and K (Liu et al., 2006). So in the QUEFTS model, two boundary lines should first be determined, and the QUEFTS model could then simulate a liner-parabolic-plateau curve for estimating optimal nutrient uptake used a solver module in Microsoft Office Excel.

For more details about the QUEFTS model, please refer to the original Janssen et al. (1990) and to Liu et al. (2006).

2.3. Model validation

The OPT for wheat in Hebei (32 plots), Henan (50 plots), Shandong (30 plots) and Shanxi provinces (10 plots) were conducted in 2010–2011 to validate the QUEFTS model. These four provinces were all in North Central China and wheat was the main crop production. Wheat was sown at the beginning of October and harvested in mid-June of the following year. The NE for Wheat decision support system was used to recommend fertilizer application based on the QUEFTS model and applied best management practices through the whole growth period. The fertilizer N recommended by NE was estimated from the yield response to applied N fertilizer and agronomic efficiency of N, and fertilizer P and K were determined from the target yield and yield response combined with optimal reciprocal internal efficiency (RIE, kg nutrient uptake in above-ground plant dry matter per ton grain produced) and nutrient balance to sustain soil fertility, i.e. P and K removal should be return back to the soil (Chuan et al., 2013; He et al., 2012), which was simulated by the QUEFTS model. 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 is the yield increase per unit of fertilizer N, P_2O_5 or K_2O applied. Urea was applied two splits or three splits depending on soil fertility or expected yield response to N (Pampolino et al., 2012), while P and K fertilizers were both broadcasted and incorporated as basal before seeding. The rates of fertilizer application were listed in Table 3. Irrigation and other cultural practices were applied using the best local management.

At harvest, three $1 \times 1\,m^2$ from a location in the middle of each plot were harvested manually to determine straw and grain yield. Harvested straw and grain samples were oven-dried at 60 °C for determination of dry matter weight. Subsamples of straw and grain were digested with H_2SO_4–H_2O_2 and N, P, and K concentration were measured using the Kjeldahl method, vanadomolybdate yellow color method, and flame spectrophotometers, respectively (Chinese Society of Soil Science, 2000). The total nutrient uptake of N, P and K were calculated as the products of the nutrient concentration multiply the plant dry weight.

The two statistical formulas of root mean square error (RMSE) and normalized-RMSE (n-RMSE) were used to evaluate the QUEFTS model and the deviation between the measured and simulated data. The deviation statistics were defined as follows:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(s_i - m_i) \wedge 2}{n}} \quad (1)$$

$$\text{Normalized RMSE} = \frac{\mathrm{RMSE}}{\bar{m}} \quad (2)$$

while s_i and m_i were the simulated and measured values, respectively, n was the number of data, and $\bar{m}$ was the mean of measured data. The RMSE measured the mean discrepancy between the simulated and measured data with the same unit, and the n-RMSE removed the unit and allowed comparison among values with different units (Liu et al., 2011a).

3. Results and discussion

3.1. Characteristics of nutrient uptake

The average grain yield (adjusted to 0.135 g water g^{-1} fresh weight) of wheat (Table 4) was 5 950 kg/ha during the 2000–2011 periods. The range was from 280 kg/ha (from a long-term field experiment) to 12 000 kg/ha (from an OPT, with balanced N, P and K, and best management) with N application rates varying from 0 to 750 kg/ha, P from 0 to 137 kg/ha, and K from 0 to 249 kg/ha. However, the average N, P and K application rates were 172, 44 and 75 kg/ha, respectively. These values seemed reasonable because the datasets collected included farmer's practice, OPT, and omission plots, so they reflected more situations than only the actual status of farmers' fertilizer application in China. The HI ranged from 0.18 to 0.69 with an average of 0.44, which was similar to the value mentioned by Ji et al. (2010) in China in the 2000s, and was higher than values in the 1980s and 1990s, which were 0.38 and 0.41, respectively. The average N, P and K mass fractions in grain were 21.2 g/kg, 5.6 g/kg and 4.3 g/kg (oven-dry weight), and in straw were 5.7 g/kg, 1.4 g/kg, and 15.5 g/kg, respectively. The total above-ground N, P and K accumulation ranged from 11 to 398 kg N/ha, 1.9 to 130.7 kg P/ha, and 11 to 438 kg K/ha. The N, P and K nutrient harvest indices (NHI, PHI and KHI, the ratio of nutrient quantity in grain and total above-ground plant) were 0.74, 0.78 and 0.21, respectively, meaning that about 74%, 78% of N and P in above-ground plant presented in the grain, and 79% of K in the straw. Therefore, grain was the primary pool for N and P, and straw for K. The quantities of P and K in the grain removed from the field were used for the assessment of fertilizer P and K replacement requirements to achieve a target yield as well as to maintain P and K in the soil.

3.2. Internal efficiency and reciprocal internal efficiency

The average internal efficiencies (IEs) were 40.1 kg grain per kg plant N, 189.5 kg grain per kg plant P and 55.8 kg grain per kg plant K, equivalent to reciprocal internal efficiencies (RIEs) of 26.4 kg for N, 6.5 kg for P and 22.0 kg for K to produce 1000 kg grain with a N:P:K ratio of 4.06:1:3.38 (Table 5). In the OPT datasets, the IEs for N, P and K were 39.4 kg grain per kg plant N, 182.6 kg grain per kg plant P, 56.4 kg grain per kg plant K, and to produce 1000 kg grain needed 25.9 kg N, 6.8 kg P and 21.0 kg K, respectively. High IEs values were mainly from the omission plots with no N, P or K fertilizer input. The ranges of IEs were narrower for the OPT datasets than for all datasets, but the differences were not significant. Liu et al. (2006) used smaller datasets from 1985 to 1995 and concluded that the average IEs for N, P and K were 40.1 kg grain per kg plant N, 269.1 kg grain per kg plant P, and 43.1 kg grain per kg plant K, equivalent to 25.8 kg for N, 3.7 kg for P, and 23.3 kg for K to produce

Table 4
Characters of nutrient uptake.

Parameter	Unit	n[a]	Mean	SD[b]	Minimum	25%Q[c]	Median	75%Q	Maximum
Grain yield	kg/ha	7517	5950	1850	280	4860	6150	7190	12,000
N rate	kg/ha	7306	172	92	0	138	180	225	750
P rate	kg/ha	7180	44	23	0	36	46	59	137
K rate	kg/ha	7002	75	57	0	0	75	125	249
Harvest Index	kg/kg	2849	0.44	0.07	0.18	0.41	0.45	0.48	0.69
N uptake in grain	kg/ha	2197	118.1	48.1	7.4	86.0	117.4	143.6	349.8
P uptake in grain	kg/ha	1577	30.0	15.0	0.4	18.5	29.2	40.7	87.3
K uptake in grain	kg/ha	1614	24.6	14.5	0.8	15.2	20.8	30.3	111.7
N uptake in straw	kg/ha	2142	38.6	17.9	2.9	27.2	36.9	47.7	143.3
P uptake in straw	kg/ha	1576	8.6	6.5	0.1	3.5	7.3	12.2	44.9
K uptake in straw	kg/ha	1620	101.3	60.4	3.3	53.5	93.2	124.2	132.1
[N] in Grain	g/kg	1990	21.2	3.9	8.5	18.9	20.8	23.0	41.4
[P] in Grain	g/kg	1496	5.6	2.3	1.1	3.6	6.0	7.2	13.5
[K] in Grain	g/kg	1557	4.3	1.8	0.5	3.1	3.9	5.3	15.6
[N] in Straw	g/kg	1869	5.7	1.6	1.4	4.7	5.5	6.6	21.0
[P] in Straw	g/kg	1491	1.4	0.8	0.1	0.6	1.4	1.5	1.9
[K] in Straw	g/kg	1552	15.5	7.9	3.3	8.8	14.8	13.0	19.8
Plant N	kg/ha	3372	161	61.2	11	120.2	160.7	196.4	398
Plant P	kg/ha	2088	41	21.3	1.9	23.2	38.6	54.5	130.7
Plant K	kg/ha	2098	136	74.0	11	81.3	125.8	174.1	438
NHI[d]	kg/kg	2413	0.74	0.08	0.25	0.71	0.76	0.79	0.94
PHI[e]	kg/kg	1594	0.78	0.10	0.29	0.74	0.78	0.85	0.99
KHI[f]	kg/kg	1636	0.21	0.10	0.01	0.14	0.19	0.25	0.52

[a] n = number of observations.
[b] SD = standard deviation.
[c] Q = quartile.
[d] NHI = nitrogen harvest index.
[e] PHI = phosphorus harvest index.
[f] KHI = potassium harvest index.

1000 kg grain in China. The differences between the two studies mainly occurred for P and K. There were several probable reasons for the different results. Firstly, the data Liu et al. (2006) collected were from 1985 to 1995, when wheat varieties may have lower yield and uptake efficiency than the newer cultivars. Secondly, in 2000s, farmer practices and field experiments usually applied more P in the soil than that applied in early years, but not as much K, so plants accumulated more P and less K. As a result, the RIE for P became higher and the RIE for K a little lower. Thirdly, in past years, the irrigation, fertilizer management, pests and diseases control were not as good as current practice, which could result in different IEs values.

3.3. *Estimating the optimum nutrient uptake for a specific target yield*

The different envelope coefficients for maximum accumulation and maximum dilution in the above-ground plant dry matter of wheat for N, P and K were shown in Fig. 2. For each nutrient, a and d values represented the maximum accumulation (equivalent to the minimum IEs) and maximum dilution (equivalent to maximum IEs) in wheat. The sensitivity of the model to a and d values was tested using the three sets. Set 1, set 2 and set 3 were calculated from excluding the upper and lower 2.5, 5 and 7.5 percentiles of all internal efficiency data as outliers when HI $\geq$ 0.40. Low HI suggested that diseases, weeds, or insect pests resulted in some yield loss. Like Witt et al. (1999) and Haefele et al. (2003), data with HI < 0.40 was excluded when determining the relationships and internal nutrient efficiencies using the QUEFTS model for wheat in China. The yield potential defined as maximum attainable yield (Liu et al., 2011b; Setiyono et al., 2011), was set at 12,000 kg/ha in North Central China as an example since the yield potential had no effect on the sensitivity testing.

With a and d coefficients derived and the yield potential set, the QUEFTS model could simulate balanced nutrient uptake requirement for N, P and K (the linear-parabolic-plateau curve) assuming under conditions where the yield was not limited by any nutrients and the crop production was managed by the best practices. The nutrient requirements calculated by the QUEFTS model were similar for all three sets (Fig. 2), except at the yield target approaching the yield potential. Since set 1 included a larger range of variability, it was then used to estimate balanced nutrient uptake

Table 5
Internal efficiency (IE, kg grain/kg nutrient) of N, P and K for wheat in China.

Dataset	Parameter	n[a]	Mean	SD[b]	Minimum	25% Q[c]	Median	75% Q	Maximum
All	IE-N[d]	3372	40.1	9.3	11.3	33.7	39.4	45.3	91.8
	IE-P[e]	2088	189.5	98.4	48.4	120.4	151.6	238.5	614.9
	IE-K[f]	2098	55.8	25.7	12.8	36.8	49.3	73.5	185.8
OPT	IE-N	241	39.4	5.6	24.4	35.6	40.0	42.5	54.3
	IE-P	201	182.6	105.6	83.1	112.2	130.9	234.1	602.0
	IE-K	238	56.4	22.2	14.3	41.1	50.1	79.4	145.2

[a] n = number of observations.
[b] SD = standard deviation.
[c] Q = quartile.
[d] IE-N = internal efficiency of nitrogen.
[e] IE-P = internal efficiency of phosphorus.
[f] IE-K = internal efficiency of potassium.

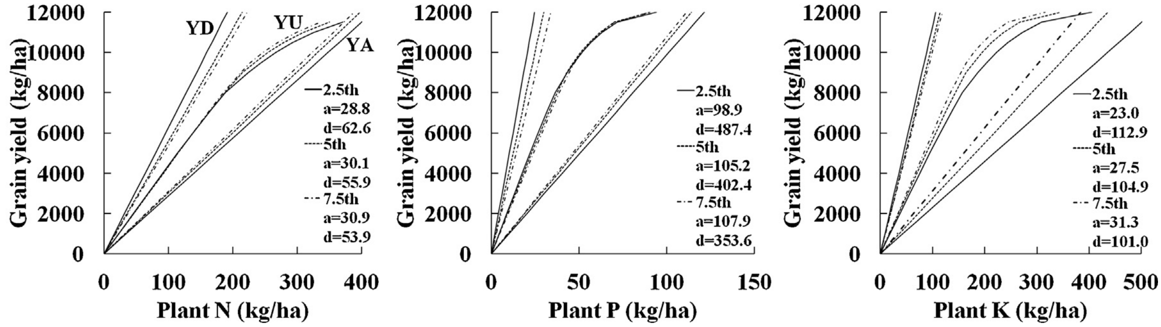

Fig. 2. Yield of wheat in relation to plant nutrient uptake at different sets of constants *a* and *d*, calculated by excluding the upper and lower 2.5 (Set 1), 5 (Set 2) and 7.5 percentiles (Set 3) of all internal efficiency data (HI ≥ 0.40). YD, YA and YU are the maximum dilution, maximum accumulation and balanced uptake of N, P and K in above-ground plant dry matter, respectively. The yield potential was set at 12,000 kg/ha as an example.

and the relationship between grain yield and nutrient accumulation. The slope coefficients of set 1 for *a* and *d* were 28.8 and 62.6 kg grain per kg N, 98.9 and 487.4 kg grain per kg P, and 23.0 and 112.9 kg grain per kg K, respectively. The QUEFTS model predicted that the balanced nutrient accumulation required to produce 1000 kg grain was 22.8 kg N, 4.4 kg P and 19.0 kg K, respectively, when the yield reached about 60-70% of potential yield. The N:P:K ratio was 5.18:1:4.32. The corresponding optimal IEs were 43.9 kg grain/kg N, 227.0 kg grain/kg P and 52.7 kg grain/kg K for balanced nutrition. The RIEs simulated by the QUEFTS model were only for the linear portion of the predicted balanced uptake line, so lower than the values derived from the data collected in Section 3.2 we described. This was confirmed by the increase as target yield increased above 60–70% of the yield potential (Buresh et al., 2010).

Mao (2003) studied that yield potential ranged from 6,000 to 12,000 kg/ha for wheat. However, regardless of the yield potential, the N:P:K ratio in the plant required to produce 1000 kg grain in the linear part of the response curve was always the same (Fig. 3a–c).

Grain nutrient removal could be simulated by the QUEFTS model (Setiyono et al., 2010). It could help to guide fertilizer application where P and K removed in the grain should be returned back to the soil by fertilizer to avoid nutrient depletion. The constants of *a* and *d* for grain nutrient removal were calculated from grain nutrient-IE (kg grain per kg nutrient in grain removed) and excluded the upper and lower 2.5 percentiles (HI ≥ 0.40). The results showed that the balanced grain nutrient removal curve was very similar to the balanced nutrient requirement for total above-ground plant under different yield potentials from 6,000 to 12,000 kg/ha (Fig. 3d–f). Regardless of the yield potential, in the linear part of the curve, the balanced N, P and K removal by 1000 kg grain were 18.3, 3.6 and 3.5 kg, respectively, and the N:P:K ratio in the grain was 5.08:1:0.97. Compared to balanced nutrient uptake in total above-ground plant, approximately 80%, 82% and 18% of N, P and K accumulated in grain and were removed from the field. These values should provide practical algorithms for fertilizer recommendation to sustain soil fertility.

3.4. Evaluation of the relationship between yield and nutrient uptake

The datasets in each envelope were from the field experiments conducted from 2000 to 2011 dealing with N, P and K treatments in China. The yield potential (defined as maximum yield) (Liu et al., 2011b; Setiyono et al., 2011) was set at 12,000 kg/ha, 10,000 and 11,000 kg/ha in North Central China, the middle and lower reaches of the Yangtze River and Northwest China,

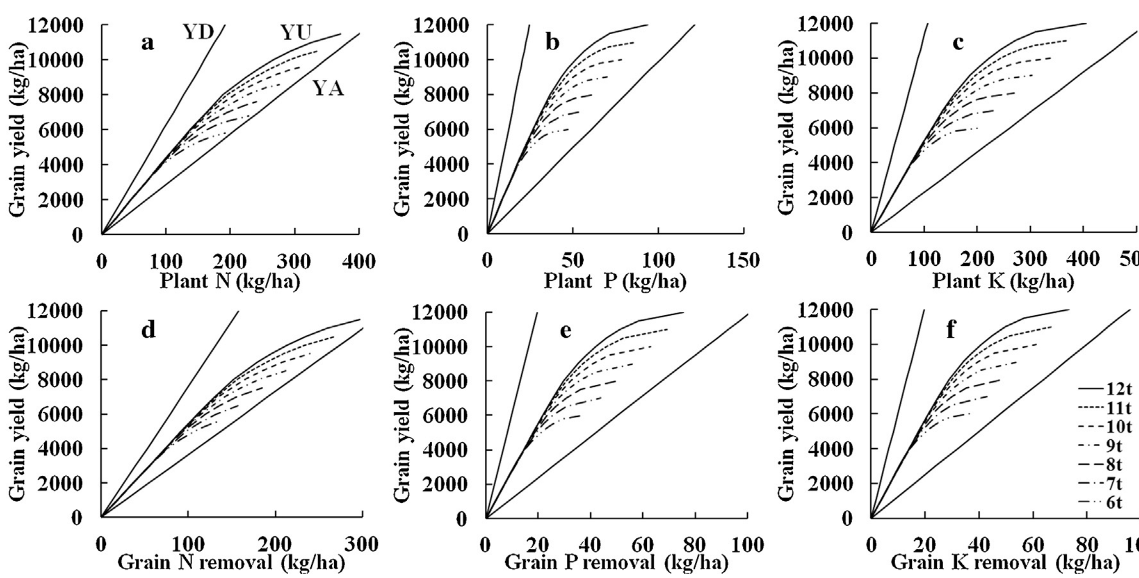

Fig. 3. Balanced nutrient requirement (a–c) and grain nutrient removal (d–f) for N, P and K under different yield potentials simulated by the QUEFTS model. YD, YA and YU are the maximum dilution, maximum accumulation and balanced uptake of N, P and K in above-ground plant dry matter or in the grain nutrient removal, respectively, which are calculated by the QUEFTS model from excluding the upper and lower 2.5 percentiles of all internal efficiency data (HI ≥ 0.40).

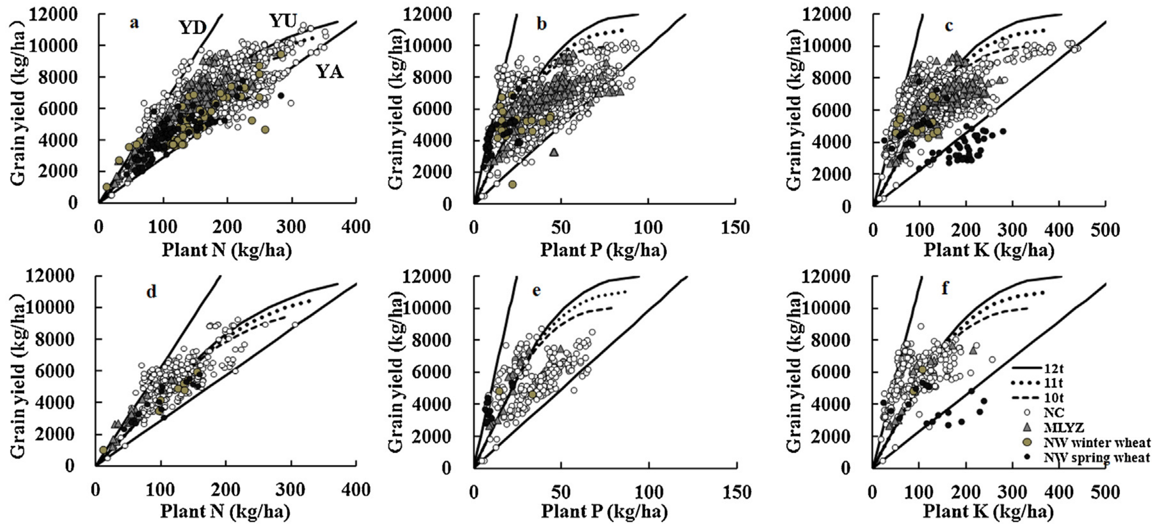

Fig. 4. Relationship between grain yield and N, P and K uptake in North Central China (NC), the middle and lower reaches of the Yangtze River (MLYR) and Northwest China (NW). The yield potential was set at 12,000, 10,000 and 11,000 kg/ha in NC, MLYR and NW, respectively. Fig. 4(a–c) were datasets from all experiments of China, and Fig. 4(e–f) were datasets from CK (unfertilized plots) and N, P or K omission plots. YD, YA and YU are the maximum dilution, maximum accumulation and balanced uptake of N, P and K in above-ground plant dry matter, respectively, which are calculated by the QUEFTS model from excluding the upper and lower 2.5 percentiles of all internal efficiency data (HI ≥ 0.40).

respectively (Fig. 4). If the dataset was above the balanced nutrient uptake line (the linear–parabolic–plateau curve) and close to the upper boundary, it meant the nutrient was deficient supply. In contrast, if the dataset was below the balanced nutrient uptake line and close to the lower boundary, it meant the nutrient was excessive supply and the yield was limited by growth factors other than this nutrient concerned. In North Central China, most N uptake was luxury, while in the middle and lower reaches of the Yangtze River, N uptake was neither luxury nor deficient, meaning that N application in this region was more rational. In Northwest China, more N uptake was excessive both in winter and spring wheat, reflecting that N fertilizer application was excessive, and should be reduced for both economic and environmental purposes (Fig. 4a).

Phosphorus accumulation in winter wheat plant showed both deficiency and luxury in North Central China, indicating that P fertilizer application was not in balance, and that it was not applied according to the soil indigenous P supply and plant demand. Some P uptake in the middle and lower reaches of the Yangtze River showed a trend to excess and in Northwest China, most spring wheat showed deficiency. The P was mainly applied as calcium superphosphate fertilizer or calcium magnesium phosphate fertilizer, or added with N or K fertilizer. For example, compound fertilizers with a N:P:K ratio of 15:15:15 used very frequently would all include more P nutrient than required for the optimum ratio. Phosphorus application should be calculated more carefully, considering soil supply and crop demand to avoid these excesses and deficiencies (Fig. 4b).

Some K uptake showed deficiency in North Central China, and only a few data sets showed luxury. However, spring wheat in Northwest China showed excessive K uptake, very unlike winter wheat (Fig. 4c). The difference may due to the environment where spring wheat was grown. The soil in Northwest China contained much K, which would result in K luxury uptake (Table 2).

Observations from unfertilized plots and N, P and K omission plots were shown in Fig. 4(d–f). Many observations were concentrated near the upper boundary line for high IEs values, reflecting severe nutrient deficiency. There were also some N accumulation data sets and more P accumulation data sets close to the lower boundary lines suggesting that there may be substantial available residual N and P in the soil leading to N and P luxury uptake from an unbalanced nutrient supply.

3.5. QUEFTS model validation

Multiple sites of the OPT plots for wheat in Hebei, Henan, Shandong and Shanxi provinces were conducted in 2010–2011 to validate the QUEFTS model. The NE for wheat decision support system was used to recommend fertilizer application based on the QUEFTS model and SSNM practices through the whole growth

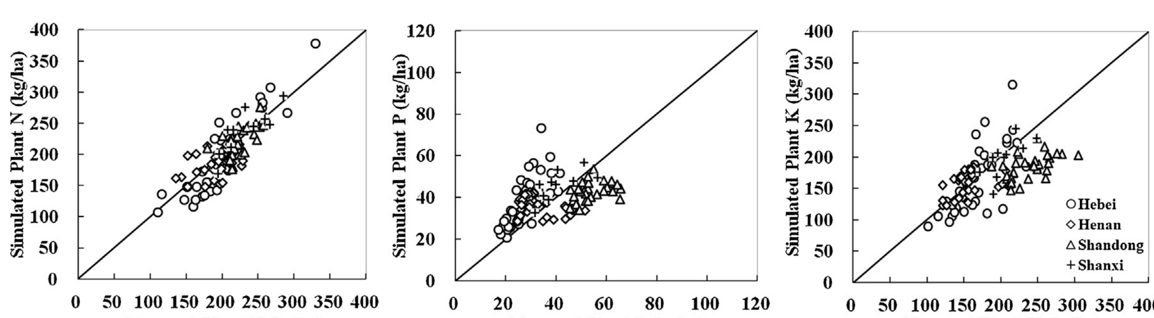

Fig. 5. Relationship between observed and simulated N, P and K uptake in above-ground plant dry matter for wheat. The average application rates of N, P and K were 135, 23 and 50 kg/ha for Hebei; 150, 32 and 62 kg/ha for Henan; 140, 34 and 58 kg/ha for Shandong; and 137, 29 and 65 kg/ha for Shanxi province, respectively.

period. The results showed that the RMSE values were 22.7, 22.4 and 93.0 for N, P and K, respectively, and the *n*-RMSE values were 10.9%, 56.9% and 47.9% for N, P and K, respectively, indicating that the P and K had a larger deviation. However, for all experiments, the observed N, P and K uptake in the above-ground plant dry matter were scattered more or less equally around the 1:1 line, suggesting that the measured values agreed well with the simulated nutrient uptake and there were no significant deviation between each other (Fig. 5), similar to the results of Liu et al. (2006) and Das et al. (2009). It confirmed that the QUEFTS model could be used to calibrate the predicted nutrient uptake and to improve fertilizer recommendations.

4. Conclusions

Based on many grain yield and nutrient uptake datasets collected from 2000 to 2011, a large range of IEs for wheat were observed. When excluded the upper and lower 2.5 percentiles of all IEs data, considering only datasets with HI $\geq$ 0.40, the QUEFTS model described the minimum and maximum internal efficiencies of N, P and K were 28.8 and 62.6 kg grain per kg N, 98.9 and 487.4 kg grain per kg P, and 23.0 and 112.9 kg grain per kg K, respectively. The model predicted a linear increase in yield if nutrients were taken up in balanced amounts of 22.8 kg N, 4.4 kg P and 19.0 kg K per 1000 kg of grain until yield reached about 60–70% of the yield potential, with a N:P:K ratio of 5.18:1:4.32. The corresponding IEs were 43.9 kg grain/kg N, 227.0 kg grain/kg P and 52.7 kg grain/kg K for balanced nutrition. The optimal N, P and K removals in 1000 kg of grain were 18.3, 3.6 and 3.5 kg, respectively, with a N:P:K ratio of 5.08:1:0.97. Compared with balanced nutrient uptake in total above-ground plant, approximately 80%, 82% and 18% of the N, P and K were presented in the grain and removed from the field.

Relationship between grain yield and nutrient uptake could be estimated for wheat in China. The results showed that most N uptake was luxury, P accumulation had both deficiency and excess, and some K uptake showed deficiency. The functions reflected the status of fertilizer application in China and served further as a tool to recommend reasonable fertilization.

Results from field validation of the QUEFTS model in four different provinces, showed a good agreement (Normalized RMSE = 10.9%, 56.9% and 47.9% for N, P and K, respectively) between observed and simulated nutrient uptake in above-ground plant. The QUEFTS model could be used as a database to support the NE for Wheat system and to recommend balanced fertilizer practices for farmers. As a result, these would help to optimize crop yield and avoid nutrient depletion or excess application, and also could improve nutrient use efficiency, economic benefits and environment sustainability.

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