Nutrient Cycling in Agroecosystems (2006) 74: 245–258
DOI 10.1007/s10705-006-9002-5

Fertilizer requirements for wheat and maize in China: the QUEFTS approach

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Received 7 August 2005; accepted in revised form 23 January 2006

Key words: China, Fertilizer requirement, Indigenous nutrient supply, Maize, QUEFTS, Wheat

Abstract

Wheat and maize are two major food crops in China. Conventional fertilizer recommendations result in higher than necessary costs to farmers and increased environmental pollution. It is essential to quantitatively estimate optimal fertilizer requirements to alleviate the problems of the two crops in China. The QUEFTS (QUantitative Evaluation of the Fertility of Tropical Soils) model was used to estimate region-specific nitrogen (N), phosphorus (P) and potassium (K) requirements as well as fertilizer applications needed to realize target yields of wheat and maize. Data of field experiments with different fertilization treatments of various regions in China during the years of 1985–1995 were used to calibrate the QUEFTS model for both wheat and maize. Minimum and maximum internal nutrient efficiencies (kg grain kg^{-1}) for the model were estimated at N (25 and 56), P (171 and 367), K (24 and 67) for wheat, and N (21 and 64), P (126 and 384), K (20 and 90) for maize. The model suggested a linear increase of grain yields for scenarios with nutrient contents of 24.6, 3.7 and 23.0 kg N, P and K per 1000 kg of wheat grain and 25.8, 4.3 and 23.1 kg N, P and K per 1000 kg of maize grain. These results suggest that the average N: P: K ratio in the plant dry matter is about 6.7: 1: 6.2 for wheat and 6.0: 1: 5.4 for maize. Relationships between internal N, P and K levels and soil properties were established and relationships between the recovery efficiencies of applied fertilizer – N, P and K were found. Running the calibrated QUEFTS model with observed field data produced a good fit between predicted and observed data. It was concluded that the calibrated QUEFTS model could be a useful tool for improving fertilizer recommendations for wheat and maize in China.

Introduction

Wheat and maize are major agricultural commodities in China and constitute a main part of the 'Green Revolution' in Asia that was brought about by the combination of improved crop varieties and improved methods of fertilizer application. Chemical fertilizers are indispensable for realizing the genetic yield potential of crops. Blanket prescriptions for fertilizer use, a common practice in China, lead to higher than necessary cost to farmers whereby excessive fertilizer inputs pose a potential environmental risk (Xie et al. 1998). All of these are compelling grounds for adopting a more flexible approach towards fertilizer use in China.

Simulation models can help to establish better fertilizer recommendations. However, most existing models describe relations between nutrient supply, nutrient uptake and crop yield only for a single nutrient. The QUEFTS (QUantitative Evaluation of the Fertility of Tropical Soils) model, developed by Janssen et al. (1990), takes interactions of N, P and K into account. QUEFTS was originally designed for quantitative forecasts of yields on unfertilized tropical soils but can be adjusted for use with other crops and soils. Smaling and Janssen (1993) applied the model to scenarios with maize in an area of Kenya, other than the area in which the original empirical relationships were tested. Witt et al. (1999) validated the model for rice using a database with more than 2000 observations made in six Asian countries, and Haefele et al. (2003) did the similar work for Sahelian systems. Pathak et al. (2003) applied the model to scenarios with wheat in India and established a working functional relationship between grain yield and N, P and K accumulation in the crop.

Wheat and maize are major food crops in China. There has been a rapid increase of fertilizer application on the two crops in recent years to achieve high yields (National Statistic Bureau 2001). As a result, excessive and imbalanced use of fertilizer is very common and the efficiency of fertilizer use is rather low in the two crops planting systems (Zhu and Chen 2002). It was thought that the QUEFTS model might shed light on this problem. However, the QUEFTS model was never used on wheat/maize systems in China. Therefore, we used our own database on wheat and maize in China to establish and verify new QUEFTS parameter values and focused on the relationship between yield and fertilizer requirements. The main aims of the current paper are to: (1) derive parameter values that enable the QUEFTS model to formulate optimum fertilizer recommendations; (2) establish maximum and minimum nutrient uptake efficiencies; and (3) give a broad overview of soil indigenous nutrient supply and the efficiencies of fertilizer element recovery by both wheat and maize.

Materials and methods

Theoretical framework

The original version of QUEFTS (Janssen et al. 1990) was developed as a tool for the quantitative prediction of maize yields on unfertilized tropical soils. The model assumes that yield is a function of the three major nutrients N, P and K supply from soil and fertilizer, taking into account the climate adjusted and variety-specific potential yield of site. For this purpose, the model calculates the potential availability of the nutrients N, P and K, and the interactions between them. QUEFTS describes the relationship between grain yield and nutrient supply into four steps: (1) assessment of the potential indigenous nutrient supply on the basis of chemical soil data; (2) calculation of the actual uptakes of N (UN), P (UP) and K (UK), based on the potential supplies of N (SN), P (SP) and K (SK), e.g., supply from soil plus fertilizer, and estimated nutrient element recovery efficiencies of applied nutrients; (3) identification of yield ranges as functions of the actual uptakes of N, P and K determined in Step 2 at maximum accumulation (in the situation where the nutrient is not limiting) and maximum dilution (in the situation where the nutrient is yield-limiting); (4) estimation of the actual yield taking into account the three yield ranges (one range each for N, P and K) identified under Step 3 and anticipated interactions between N, P and K.

In this paper, we will particularly elaborate on some assumptions made under Step 3 of the QUEFTS model dealing with the relationship between grain yield and plant nutrient accumulation. A general assumption of the model is that grain yield is only a function of N, P and K supply and potential yield (Y_{max}) determined by the crop variety and local climatic conditions (Janssen et al. 1990). Two possible (minimum and maximum) yield levels can be calculated based on the final nutrients uptake. In these calculations, the ratio of yield and nutrient, i.e., internal efficiency (IE, kg grain per kg nutrient in above-ground plant dry matter; Witt et al. 1999) would be the minimum and maximum values (YNA and YND, Figure 1). Janssen et al. (1990) assume that the relationship between grain yield and nutrient uptake follows a linear-parabolic-plateau pattern (YN, Figure 1). Since it is impossible to maximize the uptake efficiencies of all nutrients simultaneously, Janssen et al. (1992) suggest that optimal nutrient uptake can be found by maximizing the overall yield-producing uptake efficiency. The ratios of nutrient uptake over supply, i.e., UN/SN, UP/SP and UK/SK are called yield-producing uptake efficiencies. The mean of the three ratios represents the overall yield-producing uptake efficiency (TYPUE). Optimization of combinations of the three nutrients can be used to find the best N, P and K inputs by defining different values of TYPUE. In this

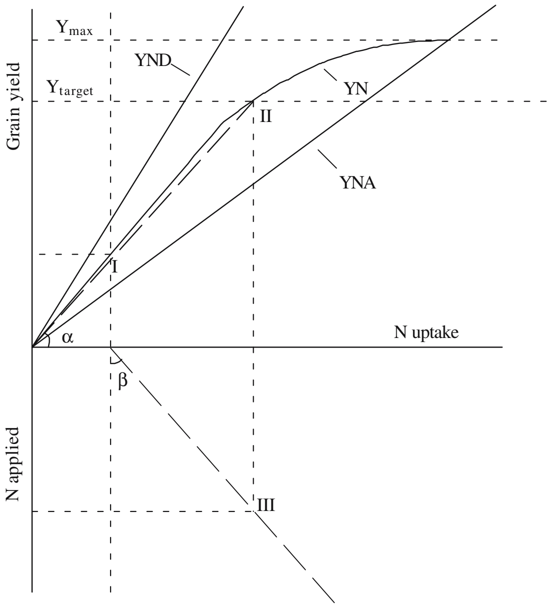

Figure 1. Schematic relationship between grain yield, N uptake and N-application. N is taken as an example, modified from the QUEFTS model proposed by Janssen et al. (1990). The boundary lines represent the maximum dilution (YND) and accumulation (YNA) of N in the above-ground dry matter. YN represents the optimum N uptake requirement to achiever a certain grain yield target (Y_{target}). Ymax is the climate adjusted yield potential.

paper, TYPUE is maximized under the constraint that UN/SN = UP/SP = UK/SK≥0.95, both for wheat and maize. The model was run several times each time slightly increasing the yield from 0 to Y_{max} and the balanced nutrient requirements for the different target yields were recorded.

As stated before, nutrient requirements can be identified by running the model for various yield targets equal to or less than a given yield potential. In Figure 1, N is taken as an example. The N requirement of crops at point I equal the soil's indigenous supply. If the target yield is less than this value, it is not necessary to apply any N fertilizer because nutrient supply by the soil can satisfy the crop's N-requirement. In point II, representing the crop's total N uptake at the target yield, this is made up of soil indigenous N and fertilizer N. The distance between points I and II indicates the quantity of N that must be furnished from fertilizer. However, it is not necessarily so that all fertilizer applied can be utilized by current season crops. Part of the fertilizer may remain unused in the soil, temporarily or permanently (Dobermann and White 1999). Hence we take the recovery efficiency of fertilizer-N into account and calculate the quantity of N fertilizer that must be applied (point III, Figure 1). Similarly, one can infer the crop's P and K requirements.

In Figure 1, α represents the internal efficiency (YN/UN) whereas β is the recovery efficiency of fertilizer-N. The value of α decreases markedly with the increasing target yield and gets to the minimum value when the target yield equals Y_{max}. Parameter β is a variable too, which depends, inter alia, on fertilizer type, amount of fertilizer applied and soil indigenous nutrient supply.

The relation between fertilizer requirement (FR), nutrient uptake (NU_{target}) at target yield (Y_{target}), soil indigenous nutrient supply (N_{ind}) and recovery efficiency (RE) are expressed by the following equations:

$$NU_{target} = Y_{target}/IEx \quad (1)$$

$$NU_{target} = N_{ind} + RE * FR \quad (2)$$

$$FR = (NU_{target} - N_{ind})/RE \quad (3)$$

Where NU_{target} is plant nutrients in the above-ground dry plant matter at maturity for target yield (kg ha^{-1}); Y_{target} is target yield (kg ha^{-1}); IEx is internal nutrient efficiency (kg grain kg^{-1} nutrient in plant dry matter); N_{ind} is soil indigenous nutrient supply (kg ha^{-1}); RE is recovery efficiency of fertilizer nutrient (kg nutrient in plant dry matter per kg of fertilizer nutrient applied); FR is fertilizer nutrient requirements (kg ha^{-1}).

Data source

The data were collected from several field experiments on wheat or maize with N, P and K applications over the period 1985 till 1995 (Zu et al. 1990; Song 1993; Li et al. 1994; Gao et al. 2000; Zhang 2003). They represent different growing environments in China, and thus covered a wide range of soils, agronomic practices and climatic conditions. Five production regions were distinguished among the data (Table 1), each representing a large area with relatively similar soils, climatic conditions and cropping systems (Figure 2). The two main production regions of wheat and maize are North and Northeast of China (NEC) and the North China Plain (NCP). The former is characterized by cool temperate with single cropping systems of spring wheat and spring maize, while the latter is dominated by a temperate climate with an annually repeated winter wheat/summer maize rotation. The production region of Southwest China (SWC) has a temperate to subtropical subhumid climate, and the rotations employed are widely diverse. The remaining two regions are from a production point of view of wheat and maize of minor importance. South China (SC) has a humid climate with many different rotations, and Northwest China (NWC) has a continental climate with usually a wheat/maize rotation, or a single cropping system of spring wheat or maize. The Tibet Plateau, has a cool temperature with only a few crops planted, however that region is not included in this study (Figure 2).

In each region, we included only data from experiments with adequate irrigation and good control of pests and diseases. At each site, experiments included a control fields (unfertilized, T0) and fields with different applications of N, P and K (fertilized, TF), which varied between in sites and years. The available data from these experiments included: (1) soil properties, such as texture, soil carbon content, pH, total N, Olsen P, exchangeable K for both TF and T0; (2) crop parameters, such as grain and straw yields; N, P and K in total above-ground plant dry matter for both TF and T0; and (3) levels of applied fertilizers for TF.

Description of field experiments

At each experimental site, the cropping systems were comparable to those local systems. All crops were grown under irrigated conditions. Weeds were controlled by hand and plant protection measures were applied to control pests and diseases. Farmers were requested to tend their wheat or maize fields and apply their own choice of fertilizers to TF plots. The range of NPK doses applied to TF plots are listed in Table 2. Fertilizers used on TF plots included urea (46% N), single super phosphate (7% P) and KCl (50% K). Half of the N was applied as a basal dressing to both crops, and the rest was top-dressed after some 150 days in the case of winter wheat, or 50 days in the case of summer maize. P and K were entirely applied as a basal application to both two crops. T0 plots received the

Table 1. Overview of experimental sites.

Region	Province	County	Rainfall(mm)	Location		Temperature (°)		Case (*n*)[a]	
				Latitude (°N)	Longitude (°E)	Minimum	Maximum	Wheat	Maize
NNC	Jilin	Yushu,Gongzhuling	730	40.87–46.30	121.63–131.32	−16	20		37
	Shanxi	Qiangjian,Luochuan (North of province)	500	34.70–39.58	107.28–111.25	−5	22	18	10
	Shannxi	Yunji,Yuncheng, Qixian,Yuci	650	34.57–40.72	110.23–114.55	−3	25	35	22
NCP	Hebei	Xianxian,Yanshan, huozhou,Xingtai	600	36.08–42.67	113.45–119.83	−4	25	37	34
	Shandong	Zhaoyuan,Zibo,Caoxian	650	34.42–38.38	114.60–112.72	−3	26	36	40
	Shanxi	Fufeng (South of province)	500	31.70–34.57	105.48–111.02	−2	27	20	16
SWC	Sichuan	Zhongjiang,Wenjiang, Meishan,Pengan	1200	26.05–34.32	97.35–100.2	4	28	78	35
	Yunnan	Chuxiong,Qujing,Lijiangna, Yanshan	1500	21.13–29.25	97.52–106.18	8	25	16	28
	Guizhou	Ziyun,Guiyang,Puding	1300	24.62–29.22	103.60–109.58	4	24	12	25
SC	Zhejiang	Fuyang,Quyang,Jinghua	1200	30.77–35.12	121.92–116.37	3	29	19	
	Jiangsu	Yizheng,Danyang,Xinhua, Yixin, Jiangning,Wuxian	1100	30.75–35.33	116.30–121.95	2	28	38	
	Hunan	Changsha,Ningxiang	1500	24.63–30.13	108.78–114.25	5	29	17	
NWC	Xingjiang	Asuke,Hetian,Jimusaer	300	37.77–47.08	75.22–89.40	−12	16	46	49

[a] the number of case indicated the observations of experiment for wheat and maize, and each observation included one control treatment (unfertilized, T0) and one treatment with applications of N, P and K (fertilized, TF). NNC – North and Northeast China; NCP – North China Plain; SWC – Southwest China; SC – South China; NWC – Northwest China.

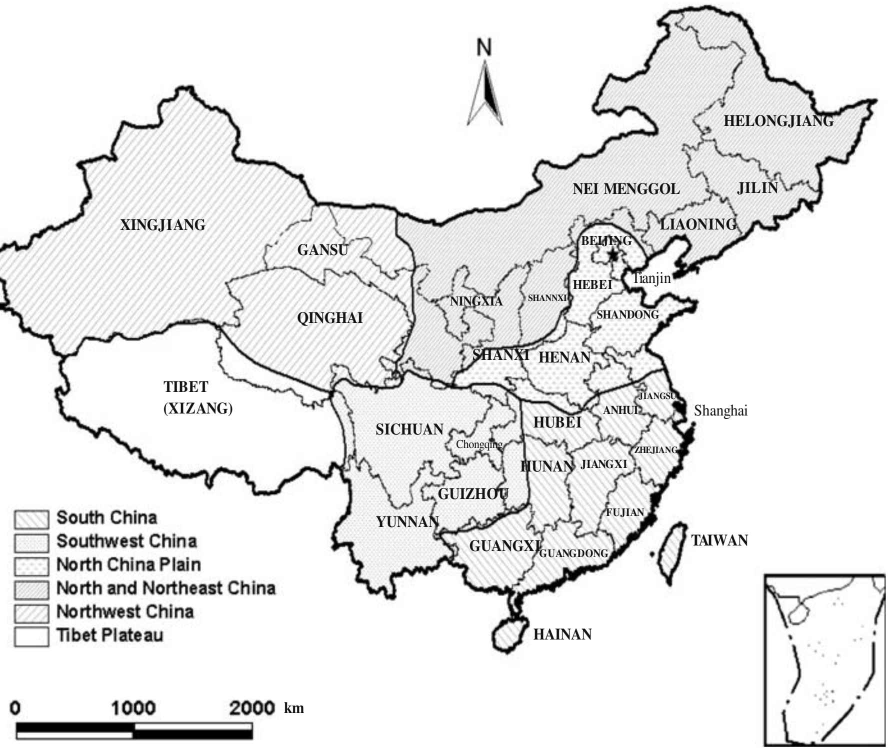

Figure 2. The distribution of different production regions in China. (Liu 1987).

same treatment as TF plots except that no fertilizer was applied. Crops were manually harvested close to the ground and grain yields on both T0 and TF plots were carefully measured.

Soil and plant sample analysis

Before setting up the experiments composite soil samples were taken of the 0–15 cm topsoil at five locations within each plot. Samples were mixed and bulked, and a representative sub-sample was taken for soil chemical analysis according to standard procedures. The dry weight of the sampled soil was determined and the samples were sieved through a 2-mm screen, mixed, air dried and analyzed for organic C (Kalembasa and Jenkinson 1973), total N (Bremner 1965), Olsen P (Olsen et al. 1954), exchangeable K (Knudsen et al. 1982) and pH (H_2O; 1:2.5 soil/water ratio). Those soil properties vary largely, such as total N from 0.37 to 2.2 g kg^{-1}, Olsen P from 1.1 to 45.1 mg kg^{-1}, exchangeable K from 0.56 to 10.7 $mmol_{(+)}$ kg^{-1} and pH from 5.0 to 9.0.

Grain and straw samples were collected from all T0 and TF plots at harvest. The grain was separated from straw using a plot thresher (wheat) or by hand (maize). Harvest indexes were determined from the oven-dry (70 °C) straw and grain yields (14% moisture content). Plant-N, P and K uptakes were determined on ground grain and straw subsamples.

Indigenous nutrient supply for a specific nutrient element is defined as the amount taken up by the crop under optimal conditions, i.e., when all other nutrients are amply supplied. Therefore, the indigenous N supply of soils was determined in samples from T0 plots. However, the indigenous P and K supply were estimated from plots not receiving P and K from fertilizers in TF treatments, respectively. Since in most soils N is the most limiting plant nutrient, this method will slightly underestimate the true soil indigenous N supply. The recovery efficiency of fertilizer N was inferred from the difference in N uptake between TF and T0. The recovery efficiencies of fertilizer P and fertilizer K were based on the different P and K uptakes from the NPK plots of TF and plots not receiving P and K from fertilizers, respectively.

Table 2. The data set on grain yield, harvest index, plant nutrients and fertilizer application used to estimate internal nutrient efficiency, base uptake from unfertilized soil (indigenous nutrient supply), reciprocal internal efficiency, nutrient recovery efficiency and the generic parameter values inferred from the original data combining the 5 regions in China.

Parameters	Wheat			Maize		
Grain yield (t ha^{-1})	0.35–8.73 (744) [a]			0.55–10.98(592)		
Harvest index (kg kg^{-1})	0.18–0.65 (744)			0.1–0.68 (592)		
	Nitrogen	Phosphorus	Potassium	Nitrogen	Phosphorus	Potassium
Nutrient uptake (kg ha^{-1})	10.4–256.9 (642)	2.8–32.9 (642)	12.8–219.6 (642)	8.42–324.8 (521)	3.14–79.8 (521)	9.3–364.0(521)
Fertilizer application (kg ha^{-1})	0–384 (372)	0–97 (372)	0–202 (372)	0–417 (296)	0–123 (296)	0–225 (296)
Internal efficiency (kg kg^{-1})	19.8–66.4	146.3–391.5	17.4–87.3	15.61–75.8	114.1–403.5	14.6–97.9
Reciprocal internal efficiencies (kg nutrient t^{-1} grain)	15.1–50.5	2.6–6.8	11.5–57.5	13.2–64.0	4.0–44.9	10.2–68.5
Indigenous nutrient supply (kg ha^{-1})	7.14–134.7 (345)	4.4–26.5 (74)	30.5–172.2 (91)	24.1–177.4 (236)	4.9–35.5 (84)	52.6–279.6 (102)
Recovery efficiency (%)	7.6–82.3	9.8–43.4	4.0–91.7	13.0–87.1	5.1–51.5	5.4–79.6
Average estimated parameters inferred from the above data						
Internal efficiency (kg kg^{-1})	40.1	269.1	43.1	42.3	254.9	50.6
Reciprocal internal efficiencies (kg nutrient t^{-1} grain)	25.8	3.7	23.3	23.6	3.9	19.8
Indigenous nutrient supply (kg ha^{-1})	54.1	14.2	93.4	75.9	16.4	147.1
Recovery efficiency (%)	45	22	47	50	24	44

[a] Number of observations in parentheses. Data are based on experiments conducted at several sites in China during the year 1985 and 1995 (see Table 1).

The harvest index (kg kg^{-1}) was calculated as the ratio of grain yield over total above-ground plant dry matter. The internal efficiency (IE, kg kg^{-1}) of N, P or K nutrients is defined as the amount of grain divided by the quantity of N, P or K present in the above-ground plant dry matter, respectively. The reciprocal value of IE (RIE, kg 1000 kg^{-1}) expresses the quantity of a particular nutrient in above-ground plant dry matter needed to produce 1000 kg of grain.

Results and discussion

General overview of the dataset

The dataset used for determining the internal nutrient efficiency, fertilizer recovery efficiency and soil indigenous nutrient supply for wheat and maize is presented in Table 2. The ideal data set for the QUEFTS model calibration would not be influenced by any limitation to crop growth and production by factors other than N, P and K supply. To remain on the safe side, we used only data sets with a harvest index ≥0.4 kg kg^{-1} and excluded 2.5% of the highest and lowest observations, as done by Witt et al. (1999), when determining borderline values for dilution and accumulation of nutrients in the plant tissue (set 1, Table 3). To assess the sensitivity of the generated relationship between grain yield and uptake of N, P and K in the model, another two constants for the model were estimated by excluding 5 and 7.5% of the highest and lowest observations, respectively (sets 2 and 3, Table 3). Set 4 in Table 3 presents parameter values that we recommend for use in QUEFTS.

Internal nutrient efficiency

The ranges of the internal nutrient efficiencies for wheat and maize are given in Table 2. Average IE of N (IEn), P (IEp) and K (IEk) based on analysis of all TF and T0 plots amounted to 40.1, 269.1 and 43.1 kg grain kg^{-1} for wheat, and 42.3, 254.9 and 50.6 kg grain kg^{-1} for maize. To produce 1000 kg grain yield, one would need 25.8, 3.7 and 23.3 kg of N, P and K for wheat, and 23.6, 3.9 and 19.8 kg of N, P and K for maize. The IE values of wheat and maize are rather similar. Both maximum and minimum values of P-uptake for maize are lower than the values suggested by Janssen et al. (1990), but similar suggestions were put forward by Saidou et al. (2003). And the low IEp of maize tallies with values proposed in Chinese literature (Li et al.1990; Yang 1991). The IE 'borderline'-values of N, P and K for wheat are close to values suggested by Pathak et al. (2003).

Figure 3(a–c) shows the relationship between grain yield and nutrient accumulation in wheat plant matter at maturity; Figure 3(d–f) shows the same for maize. Mean IEn-values from T0 plots were higher than those from TF plots for both wheat and maize, possibly because of the high C/N quotient in T0 plots. However, the mean IEp and IEk values found for T0 plots were lower than for

Table 3. Constants[a] of borderline functions relating grain yield to the maximum accumulation (a) and dilution (d) of N, Pand K in the above-ground plant dry matter of wheat and maize.

Nutrients	Set 1		Set 2		Set 3		Set 4[a]	
	a (2.5th)	d (97.5th)	a (5th)	d (95th)	a (7.5th)	d (92.5th)	a	d
Wheat								
N	24.5	55.6	27.5	51.3	29.4	48.7	25	56
P	171.5	366.9	188.9	340.2	202.2	332.1	171	367
K	23.5	66.7	26.0	64.6	29.8	61.4	24	67
Maize								
N	20.5	64.2	23.8	58.4	28.1	54.3	21	64
P	126.0	383.8	145.1	361.7	162.3	332.4	126	384
K	19.0	90.3	25.5	81.1	31.0	75.1	20	90

[a]Data with an harvest index of < 0.4 were excluded. Constants a and d were calculated by excluding the upper and lower 2.5, 5 or 7.5 percentiles of all internal nutrient efficiency data presented in Table 2 . [b]Recommended standard parameters of the ‚a' and ‚d' values for wheat and maize. All *r* values, which are the minimum N, P and K uptake required to produce any measurable grain yield in Step 2 of the QUEFTS model were set to zero for both wheat and maize in this study due to absence of sound estimations (Witt et al. 1999).

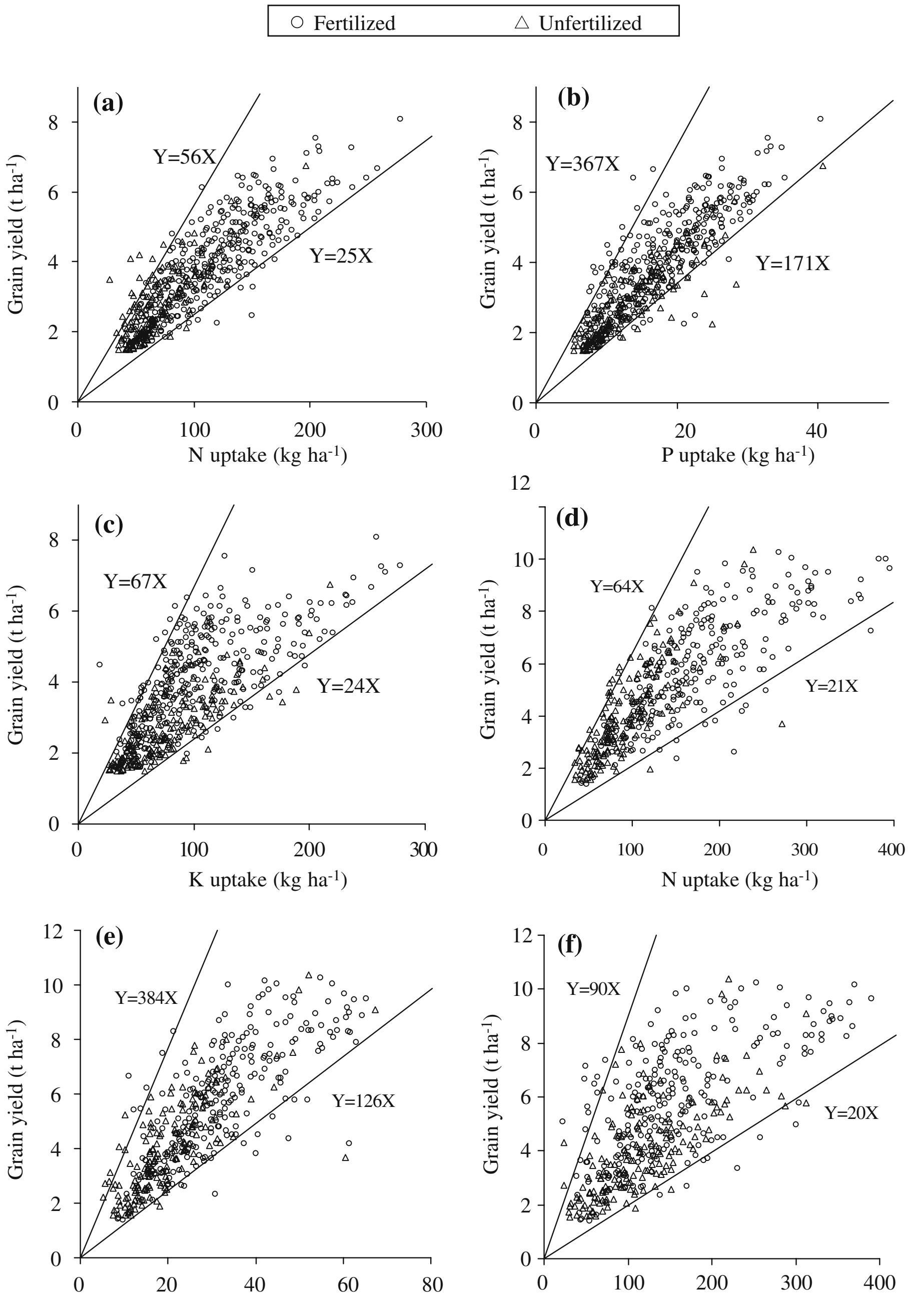

Figure 3. The relationship between grain yield and accumulation of N, P and K in wheat (a–c) and maize (d–f). based on data from Table 2 ('○' from TF plots, and △ from T0 plots). The upper and lower lines indicate yields with maximum dilution and maximum nutrient concentrations used are those in Set 4 (Table 3).

TF plots, assumedly because P and K are rarely the limiting nutrients at those locations.

To test the sensitivity of the model to boundary values of nutrient accumulation, we ran the model with parameter sets 1, 2 and 3 presented in Table 3 whereby the potential yields of wheat and maize were both set to 10 t ha^{-1}. We found that differences in stepwise exclusion of extreme data (see

Table 3) greatly affected the slope of the boundary. However, the optimal nutrient requirements for wheat calculated by the model were similar for all three sets of lines (Figure 4(a–c)). Differences were greatest at yield targets that were close to the yield potential. This is because the elimination of the upper and lower IE values only narrowed the borderlines and the distribution of the IEs had little effect on the model output. Similar findings have been published by Witt et al. (1999) for rice and by Pathak et al. (2003) for wheat. Correspondingly, we obtained a similar figure for maize (Figure 4(d–f)). Taking into consideration that there is considerable variation of the internal efficiencies at farmer's fields, we presumed that set 4 (Table 3) could be used as standard parameter set in QUEFTS for wheat as well as maize.

Nutrient requirements as affected by the potential yield

QUEFTS calculates nutrient requirements to achieve a certain yield target that is co-determined by the limits to the potential yield. There are considerable differences in the potential yield figures for wheat and maize varieties that are currently grown from the north to the south of China. Potential yield figures range from 6 to 12 t ha^{-1} for wheat (Mao 2003) and from 7 to 13 t ha^{-1} for maize (Zhang 2001). Figure 5 illustrates the nutrient requirements at different potential yields. The relationship between grain yield and nutrient accumulation as predicted by QUEFTS is linear at lower yield levels (Figure 5). This pertains to a situation where plant growth is mainly limited by nutrient supply. As the target yields become closer to the yield potential, IE values decrease markedly. This trend was also observed by Witt et al. (1999) for rice and Pathak et al. (2003) for wheat. Regardless of the yield potential, calculated optimal N:P:K ratios in plant matter were 6.7:1:6.2 for wheat and 6.0:1:5.4 for maize, similar to the average plant N:P:K ratio of 6.9:1:6.3 for wheat and 6.0:1:5.0 for maize derived from the basic data set. In the linear trajectory, input requirements for 1000 kg of grain would be 24.6, 3.7 and 23.0 kg N, P and K for wheat, and 25.8, 4.3 and 23.1 kg N, P

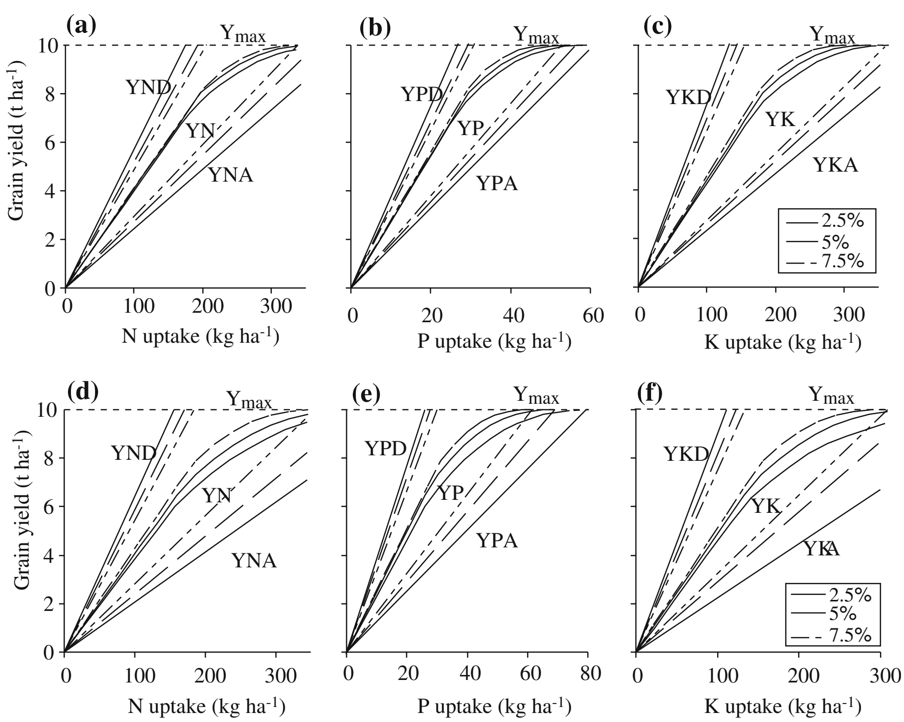

Figure 4. Yield of wheat (a–c) and maize (d–f) in relation to plant nutrients using sets of 1, 2 and 3 from Table 2, calculated with exclusion of the upper and lower 2.5 (Set 1), 5 (Set 2), and 7.5 (Set 3) percentiles of all internal efficiency data. The upper and lower lines indicate yields with maximum dilution and maximum nutrient concentrations, respectively.

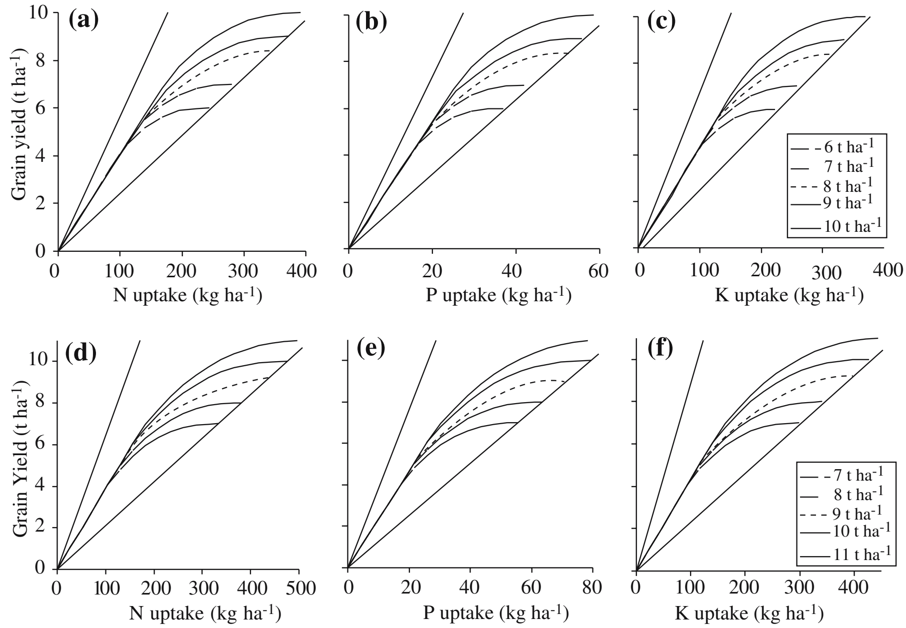

Figure 5. N, P and K uptake requirements for target grain yields as function of the yield potential (6,7,8,9,10 t ha^{-1}) for wheat (a–c), and (7,8,9,10,11 t ha^{-1}) for maize (d–f). The upper and lower boundaries were calculated using recommended values (Set 4, Table 3).

and K for maize regardless of the yield potential. The corresponding IE values for N, P and K were 40.7, 271.8 and 43.5 kg kg^{-1} for wheat and 38.8, 232.9 and 43.4 for maize. Both nutrient uptake and IE values of wheat and maize are similar to the values derived from the observations (Table 2). In the calculations, the linear trajectory is always about 80% of the whole range, both for wheat and maize. These findings are consistent with the results reported by Witt et al. (1999) for rice. Beyond the linear trajectory, IE values decrease sharply to reach minimum values at potential yield.

Soil indigenous nutrient supply and nutrient recovery efficiency

T0 plots are widely used to estimate indigenous N supply (INS) by the soil under the assumption that N would be the dominant nutrient element to limit crop growth (Cassman et al. 1996). This harbors the danger of a significant underestimation of soil indigenous P (IPS) and soil indigenous K supply (IKS) in such plots. Therefore INS was estimated from T0 plots, whereas IPS and IKS were estimated from plots not receiving P and K from fertilizer in TF fields, respectively. Note that INS, IPS and IKS varied widely for both wheat and maize in our data set (Table 2); the mean INS, IPS and IKS values were 54.1, 14.2 and 93.4 kg ha^{-1} for wheat, and 75.9, 16.4 and 147.1 kg ha^{-1} for maize. The soil indigenous nutrient supply was plotted against all available combinations of soil test values. The regression equations and their correlation coefficients from 5 different regions are presented in Table 4. The equations are simple compared to those developed by Janssen et al. (1990). Adding other soil test values, however, did not improve the explanation of soil indigenous nutrients supply.

Recovery efficiencies varied widely for wheat and maize at all sites. The mean recovery efficiencies of N, P and K observed in the experiments were 45, 22 and 47% for wheat and 50, 24 and 44% for maize (Table 2). Understandably, REn, REp and REk varied considerably with the quantity of fertilizer applied. The relationship between fertilizers application and the recovery efficiency of wheat and maize was established as suggested by Pathak et al. (2003). Rather than using the constants for recovery efficiency, which were originally determined by Janssen et al. (1990), i.e., 0.5, 0.1 and 0.5 for REn, REp and REk, we prefer to use the relationship presented in Table 5.

Table 4. Soil indigenous N, P and K supply (kg ha^{-1}) from 5 regions to wheat and maize, expressed in soil chemical properties.

Region	Wheat			Maize		
	Regression equations	*n*	R^2	Regression equations	*n*	R^2
NNC	INS = 22.32 TotalN + 47.78	49	0.41*	INS = 28.98 TotalN + 61.50	51	0.53**
	IPS = 0.36 OlsenP + 12.33	15	0.63**	IPS = 0.46 OlsenP + 16.42	19	0.62**
	IKS = 8.01 Ex.K + 59.76	21	0.55**	IKS = 7.98 Ex.K + 95.97	27	0.78**
NCP	INS = 34.62 TotalN + 32.06	89	0.47**	INS = 21.88 TotalN + 55.14	74	0.59**
	IPS = 0.33 OlsenP + 9.61	18	0.66**	IPS = 0.55 OlsenP + 11.81	30	0.51**
	IKS = 25.96 Ex.K + 34.74	24	0.50**	IKS = 31.67 Ex.K + 70.69	33	0.60**
SWC	INS = 30.73 TotalN + 11.20	98	0.55**	INS = 8.61 TotalN + 19.71	68	0.44*
	IPS = 0.55 OlsenP + 4.37	18	0.62**	IPS = 0.38 OlsenP + 5.70	23	0.48**
	IKS = 5.79 Ex.K + 45.20	19	0.71**	IKS = 19.21 Ex.K + 48.94	31	0.69**
SC	INS = 32.81 TotalN + 2.37	68	0.57**	–		
	IPS = 0.24 OlsenP + 3.39	14	0.72**	–		
	IKS = 14.99 Ex.K + 10.60	15	0.79**	–		
NWC	INS = 38.63 TotalN + 31.26	41	0.49**	INS = 28.68 TotalN + 38.62	43	0.51**
	IPS = 0.26 OlsenP + 6.22	9	0.78**	IPS = 0.22 OlsenP + 10.76	12	0.72**
	IKS = 6.01 Ex.K + 43.36	12	0.67**	IKS = 12.68 Ex.K + 98.78	11	0.83**

*p < 0.05, **p < 0.01. INS, IPS and IKS are soil indigenous N, P and K supply (kg ha^{-1}), respectively. Total.N (g kg^{-1}), Olsen.P (mg kg^{-1}) and Exchangeable K ($mmol_{(+)}$ kg^{-1}) are soil chemical properties. NNC – North and Northeast China; NCP – North China Plain; SWC – Southwest China; SC – South China; NWC – Northwest China. – Data absence, we recommended that the soil indigenous N, P and K supply to maize in the region of South China can use the results from the region of South China (SC).

Table 5. Relationship between recovery efficiency (%) and fertilizer application (kg ha^{-1}) for wheat and maize.

Wheat			Maize		
Regression equations	*n*	R^2	Regression equations	*n*	R^2
$REn = 3\times10^{-4}\times FN^2 - 0.28\times FN + 85$	127	0.83**	$REn = 1\times10^{-4}\times FN^2 - 0.21\times FN + 86$	76	0.61**
$REp = 2\times10^{-3}\times FP^2 - 0.51\times FP + 43$	53	0.72**	$REp = 2\times10^{-3}\times FP^2 - 0.49\times FP + 45$	57	0.65**
$REk = 4\times10^{-4}\times Fk^2 - 0.34\times FK + 87$	64	0.63**	$REk = 2\times10^{-4}\times FK^2 - 0.21\times FK + 76$	69	0.56**

**p < 0.01. REn, REp and REk are recovery efficiencies of N, P and K (%), respectively, FN, FP and FK are fertilization application (kg ha^{-1}), respectively.

Model validations

QUEFTS was calibrated with the relations discussed above. The relations between yield and the maximum accumulation and dilution of N, P and K in the above-ground plant dry matter of wheat and maize can be calculated using the recommended values (Set 4, Table 3), respectively. Indigenous supply from different regions for N, P and K can be estimated using Equations in Table 4, while estimates of recovery efficiency of applied N, P and K can be obtained from Equations in Table 5. The fertilizer requirement can be calculated with the Equations 1, 2 and 3.

Data on wheat and maize production from different regions and varying fertilizer application practices were selected to test the QUEFTS model. The selected sites are summarized in Table 6. These environments represent a wide range of soil characteristics and thus a significant challenge to the model. One of detailed example for the validation of the model has been presented for wheat with data from Quzhou county in Hebei province of the North China Plain (Table 7). Imbalanced fertilizer application produce the actual yield of 5003.2 kg ha^{-1} while the model predicted a yield of 4982.8 kg ha^{-1} (Table 7). Yields of wheat and maize calculated by the model from different sites showed also good agreement with measured values for both wheat and maize (Figure 6). However, the actual fertilizer application rates conducted by farmers are not always in agreement with the recommended application rates calculated by the model. The difference is most likely caused by

Table 6. Selected experimental sites used for model validation.

Region	Location	Latitude (°N)	Longitude (°E)	Elevation (m)	Rotation system
NNC	Shuangcheng county, Hilongjiang province	45.38	126.3	180	wheat*
	Qixian county, Shannxi province	37.36	112.33	760	maize*
NCP	Quzhou county, Hebei province [1]	36.87	115.02	40	wheat*/maize*
	Wuqiao county, Hebei province [2]	37.3	116.4	29	wheat*/maize*
SWC	Yanshan county, Yunnan province	23.62	104.33	1450	maize*
	Wenjiang County, Sichuan province	30.97	103.81	530	wheat*/rice
SC	Xinghua county, Jiangsu province	32.93	119.83	3	wheat*/rice
	Changsha county, Hunan province	28.23	112.87	55	maize*/rice
NWC	Akesu county, Xingjiang province	41.15	80.3	1100	wheat*/maize*

*Crop used for model validation. [1,2] Data from long-term site-specific nutrient experiment conducted at China Agricultural University experimental station in Quzhou and Wuqiao counties, Hebei province. NNC – North and Northeast China; NCP – North China Plain; SWC – Southwest China; SC – South China; NWC – Northwest China.

Table 7 Yield of summer wheat predicted by the QUEFTS model in Quzhou County in Hebei province in the North China Plain (NCP).

Nutrient	Nutrient supply (kg ha^{-1})		Nutrient uptake predicted (kg ha^{-1})	Yield predicted (kg ha^{-1})
	Soil indigenous[a]	Fertilizer [b]		
N	64.3	71.1	125.8	4982.8
P	13.9	8.5	20.4	
K	100.0	0	97.6	

[a] Soil chemical properties of Total.N, Olsen.P and Exchangeable K are 0.93 g kg^{-1}, 12.91 mg kg^{-1} and 2.51 mmol$_{(+)}$ kg^{-1}, respectively. [b] The N, P and K fertilizer applications are 135.0, 28.0 and 0 kg ha^{-1}, respectively. [c] The measured yield is 5003.2 kg ha^{-1}. The maize yield potential was set to 10 t ha^{-1} (Y_{max}).

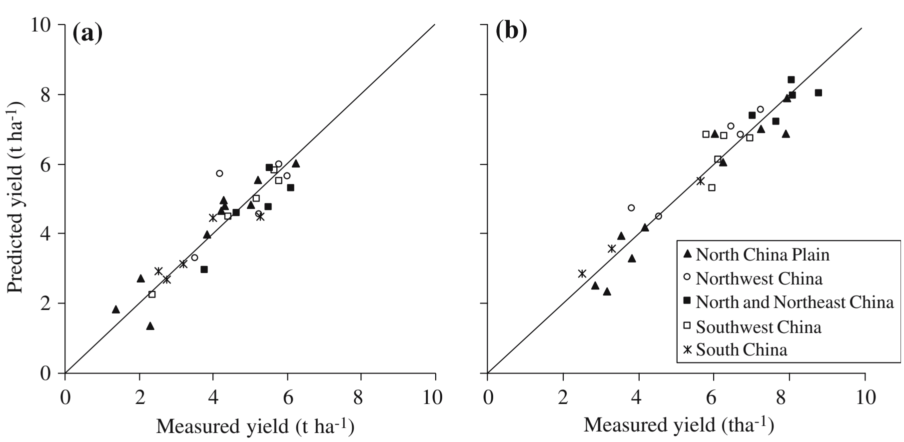

Figure 6. Relation between measured and predicted yield by QUEFTS model for wheat (a) and maize (b) in different locations in China.

imbalanced fertilizer application at farmers' fields. It may be more profitable for farmers to maximize nutrient efficiencies by a more balanced nutrition than to aim at higher yield targets in seasons with yield levels approaching maximum yields.

Conclusions

Based on data which are thought to represent the main wheat and maize cultivation areas in China, the QUEFTS model was used to estimate the nutrient requirements of wheat and maize, taking interactions between N, P and K into account. This has resulted in a useful tool to identify nutrient requirements for target yields of winter wheat and maize. Data collected from field experiments in the wheat and maize cultivation areas of China during the years of 1985 to 1995 were used to calibrate the QUEFTS model. We propose to use N(25 and 56), P(171 and 367), K(24 and 67) for wheat, and N(21 and 64), P(126 and 384), K(20 and 90) for maize as standard QUEFTS model borderline values describing the minimum and maximum internal efficiencies. The model suggests a liner increase in grain yield with N, P and K inputs of 24.6, 3.7 and 23.0 kg N, P and K for wheat, and 25.8, 4.3 and 23.1 kg N, P and K for maize per 1000 kg grain yield. The calculations suggest that the average N:P:K ratio in plant matter is about 6.7:1:6.2 for wheat and 6.0:1:5.4 for maize. The relationships between soil-N, P and K supply and soil properties were established and recovery efficiencies of N, P and K could be related to application specifications rather than using generic constants as in the original model. Inputting experimental data into the calibrated QUEFTS model yielded consistent results that were close to the observed ones.

In summary, it is felt that the study can help to improve the formulation of fertilizer strategies that suit local conditions and farmers' needs. The calibrated QUEFTS model can be used to develop fertilizer application strategies for different wheat and maize cultivation areas in China. It also can serve to evaluate standard or generic fertilizer recommendations. In this way fertilizer use can be adjusted to the biophysical and socioeconomic environment in which the two crops are grown.

Acknowledgements

This research supported by the National Basic Research Program of China (Project 2005CB121103) and the Sino-Dutch Project (LUW/CHI/971) founded by the Dutch SAIL foundation and Chinese Ministry of Education (985 project). The authors also thank Prof. P.M. Driessen, Department of Environmental sciences, Wageningen University, The Netherlands, for his correction of English on the manuscript. We furthermore like to thank the unknown reviewers and the editor for their valuable comments, which were of great help in improving the manuscript.

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