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CROPS AND SOILS RESEARCH PAPER

Estimating nutrient requirements for winter oilseed rape based on QUEFTS analysis

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SUMMARY

Estimating crop nutrient requirements for winter oilseed rape (*Brassica napus* L.) is a crucial step in optimizing fertilization to enhance seed yield and improve fertilizer use efficiency. In the present paper, a database composed of 1035 on-farm observations collected from 2005 to 2010 across the major winter oilseed rape production regions in China was used to evaluate internal nutrient efficiencies (kg seed per kg nutrient in plant dry matter); then the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model for winter oilseed rape was developed to describe the nutrient uptake-yield relationship of oilseed rape over a wide range of environmental conditions and predict the nutrient requirements for a target yield. After excluding observations with low harvest index values, <0·20, and excluding 0·025 of the highest and lowest internal nutrient efficiencies, the minimum and maximum internal nutrient efficiencies were estimated as 13·1 and 31·6 kg seed/kg nitrogen (N), 68·9 and 200·3 kg seed/kg phosphorus (P) and 8·9 and 31·1 kg seed/kg potassium (K), respectively. On the basis of the data settings, the balanced N, P and K uptake at different yield potential levels was calculated using a linear–parabolic–plateau curve with the QUEFTS model. Crop nutrient requirements increased linearly until the yield reached approximately 0·60–0·70 of the potential yield, and 46·0 kg N, 8·0 kg P and 57·1 kg K were found to be needed to produce 1000 kg of seed. The corresponding internal nutrient efficiencies were 21·8, 125·1 and 17·5 kg seed/kg N, P and K, respectively. However, when the target yields approached the yield potential, a decrease in internal nutrient efficiencies was detected in the model. The predicted nutrient requirement values simulated by the QUEFTS model compared well with observed values across a range of conditions. To conclude, the QUEFTS model was shown to be a practical and robust tool for assessing the crop nutrient requirements of winter oilseed rape.

INTRODUCTION

Oilseed rape, the second largest oilseed crop produced worldwide, not only furnishes edible oil for human consumption but also is a promising biodiesel crop. Over the past 40 years, world rapeseed production has increased threefold, and the average rapeseed yield has also increased by 3·4% per year (Rondanini *et al*. 2012). The demand for rapeseed will continue to increase in the coming decades as a result of increased food and energy needs associated with the expansion of the global population. Reliance on use of mineral fertilizer has made an unquestionable contribution to support high oilseed rape production (Ozer 2003; Rathke *et al*. 2005; Zou *et al*. 2009). The fertilizer industry is developing rapidly, but fertilizer management approaches remain imperfect, resulting in low nutrient use efficiencies and consequent environmental hazards (Ju *et al*. 2006; Guo *et al*. 2010). In addition, insufficient fertilizer inputs are common in some parts of the developing world, such as Africa and low-income countries in Asia (Hossain & Singh 2000; Vitousek *et al*. 2009) and for certain crops (such as oil crops) in China (Ren *et al*. 2013). Matching fertilizer inputs to crop requirements is a key component of integrated

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nutrient management, which is crucial to achieving high yields together with high resource use efficiencies and minimal environmental impacts (Chen *et al*. 2011; Zhang *et al*. 2011). Thus, understanding the crop nutrient requirements and yield–uptake relations of oilseed rape is important for integrated nutrient management to improve rapeseed yield and achieve sustainable development of oilseed rape production.

The nutrient requirements of oilseed rape are substantial (200–300 kg nitrogen (N)/ha, 39–57 kg phosphorus (P)/ha and 292–375 kg potassium (K)/ha) and higher than those of cereal crops (Orlovius 2003; Brennan & Bolland 2009). Many studies on the crop nutrient requirements of field and potted oilseed rape have been presented (Barraclough 1989; Taylor *et al*. 1991; Fismes *et al*. 2000; Orlovius 2003; Brennan & Bolland 2009). High variability in the crop nutrient requirements with respect to soil, cultivar, climate conditions, fertilizer inputs, yield level and crop management practices have also been detected (Berry *et al*. 2010; Schulte auf'm Erley *et al*. 2011; Kessel *et al*. 2012). The interactions among N, P and K fertilizer were always significant for rapeseed yields (Brennan & Bolland 2007*a*, *b*), however, crop nutrient requirements have been neglected in these trials. In addition, crop nutrient requirements are not always linearly related to seed yield (Taylor *et al*. 1991). Thus, the results of potted or field trials conducted at relatively few locations with specific soil and environment conditions and agronomic practices may not produce accurate estimation of the crop nutrient uptake of modern high-yielding varieties. Few studies have endeavoured to demonstrate the nutrient uptake–yield relationship of oilseed rape over a wide range of environmental conditions.

The Quantitative Evaluation of the Fertility of Tropical Soil (QUEFTS) model (Janssen *et al*. 1990), modified by Witt *et al*. (1999), provides an approach to estimating crop nutrient requirements for a target yield level while accounting for the interactions among macronutrients that affect plants' internal efficiencies. In the model, two linear borderlines are utilized to define the range between maximum nutrient accumulation and maximum nutrient dilution in the plant. These envelopes are arithmetically integrated with linear–parabolic–plateau curves to predict the relationship between grain yield and crop nutrient uptake and to estimate balanced nutrient requirements. The QUEFTS approach has been employed to estimate crop nutrient requirements in studies on rice, maize and wheat (Witt *et al*. 1999; Liu *et al*. 2006; Tabi *et al*. 2008; Setiyono *et al*. 2010; Zhang *et al*. 2012). The present study relied on a large database of seed yield and nutrient uptake levels for winter oilseed rape for various fertilizer management practices in on-farm experiments around the Yangtze River Basin, where 0·91 of all of China's oilseed rape is produced. A wide seed yield range is covered in the database, so it can therefore be used to examine the relationship between nutrient uptake and seed yield for winter oilseed rape. The objectives of the present study were to: (1) investigate the relationship between seed yield and shoot nutrient accumulation of winter oilseed rape and determine the standardized coefficients of the QUEFTS model for winter oilseed rape and (2) quantify the oilseed rape nutrient requirements for a specific target yield using the QUEFTS model.

MATERIALS AND METHODS

Data source

The database used for the present study included a total of 1035 on-farm observations of seed yield, straw yield and nutrient concentrations for winter oilseed rape, collected from numerous studies conducted around the Yangtze River Basin between 2005 and 2010 (Zou 2010; Wang 2014). In these regions, rainfed oilseed rape is usually transplanted to diminish the crop main-field duration and permit multiple cropping systems with limited crop land availability. Transplanting can also reduce the negative impacts on seedlings of abrupt temperature changes in winter and can help to achieve high yields. Normally, farmers sow oilseed rape seeds in nursery beds in the middle of September and then transplant seedlings when they are 30–40 days old and have 4–5 leaves. The seedlings are transplanted in the field by hand at a density of *c*. 105 000 plants/ha. The plants usually flower in the middle of March the following year and are harvested in early May. At all sites, local commercially available 'double-low' rapeseed cultivars of *Brassica napus* L. (i.e. with low glucosinolate and erucic acid contents), including the Huashuang (HS), Huayouza (HYZ), Zhongshuang (ZS) and Zhongyouza (ZYZ) varieties, are widely cultivated and seed yields vary from 0·96 to 2·44 t/ha and average 1·75 t/ha.

Data were collected from on-farm experiments conducted at 213 sites over the course of 6 years.

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The sites were located throughout Sichuan, Chongqing, Guizhou, Hubei, Hunan, Henan, Anhui, Jiangxi, Jiangsu and Zhejiang Provinces around the Yangtze River Basin (Fig. 1). These experimental sites represent a wide range of environments and soil types across the dominant winter oilseed rape production region of the Yangtze River Basin (Table 1). The experiments encompassed various fertilizer treatments to evaluate a wide range of nutrient accumulation and dilution conditions for winter oilseed rape. The treatments were: (1) OPT: the optimal fertilizer application rates for winter oilseed rape are 180 kg N/ha, 90 kg P_2O_5/ha and 120 kg K_2O/ha, according to 'Fertilizer Recommendations for Major Crops in China' (Zhang *et al*. 2009). Compared with the farmers' fertilization practices (FFP), the recommended fertilization rates improved the seed yield significantly, by 29·1% on average, and could be used as the regional mean optimal fertilization rates for winter oilseed rape in the Yangtze River Basin (Zou 2010). (2) 0-N: only P (90 kg P_2O_5/ha) and K (120 kg K_2O/ha) were applied in this treatment, to ensure that nutrients other than N did not limit plant growth and seed yield. (3) 0-P: only N (180 kg N/ha) and K (120 kg K_2O/ha) were applied. (4) 0-K: only N (180 kg N/ha) and P (90 kg P_2O_5/ha) were applied. (5) FFP: the farmers' fertilizer application rates were based on responses from a survey of 30 farmers at each site. The FFP rates between 2005 and 2010 ranged from 80 to 365, 9 to 126 and 0 to 94 kg/ha of N, P_2O_5 and K_2O, with averages of 162 kg N/ha, 50 kg P_2O_5/ha and 49 kg K_2O /ha, respectively. The results were similar to a survey conducted by H. L. Xu (personal communication). (6) CK: no fertilization.

At each experimental site, at least two treatments mentioned above were configured according to a completely randomized block design with three replicates. For all of the treatments described above, all P fertilizers and 0·60 of the N and K fertilizers were applied to the fields as a base fertilizer 2 days before transplanting. The remaining N and K fertilizers were top-dressed during the over-wintering period (growth stage (GS) 29; BBCH 1997) (0·20) and at the initiation of stem elongation (GS 30) (0·20), respectively. The N, P, K and boron (B) fertilizers applied in the experiments were urea (46% N), superphosphate (12% P_2O_5), potassium chloride (60% K_2O) and borax (11% B), respectively. Farmers followed common methods of herbicide application, and pest and disease control for all plots.

The same plant sampling protocol was followed at all experimental sites. All of the plants in each 20-m^2 experimental plot were harvested by hand to estimate the seed yields. The seeds were cleaned by hand, oven-dried at 60 °C until a constant weight was reached, and weighed. Eight oilseed rape plants were collected at harvest for the measurement of above-ground dry matter (DM), harvest index (HI) and the nutrient concentrations in the plant tissues, including stem, pod wall and seed. Straw yields were estimated based on the oven-dried seed yields of the plots and the HI of an eight-plant sample. Plant samples were digested with sulphuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2) following the method of Thomas *et al*. (1967), after which they were analysed for N and P concentrations using a flow injection analyser (FIAstar 5000, FOSS, Hillerod, Denmark). Potassium concentrations were analysed using a flame photometer. Nutrient uptake was calculated as the product of the above-ground DM contents and the total nutrient concentrations in the different plant parts.

Model development

The QUEFTS model, modified by Witt *et al*. (1999), was used to estimate relationships between crop yield and shoot nutrient uptake following five steps: (1) estimate the plant available soil nutrient supplies of N, P and K according to soil tests or from nutrient accumulation in nutrient omission plots. Here nutrient uptake measured in the nutrient omission plots (plots without fertilizer application of one of the key macronutrients) was used to assess the plant-available soil nutrient supplies (Wang *et al*. 2001); (2) calculate the actual nutrient uptake depending on the potential nutrient supplies, i.e., the plant-available soil nutrient supply in Step 1 plus the effective nutrient supply from fertilizer. Here the basic assumption is that the relationship between the actual nutrient uptake and the potential nutrient supplies is parabolic. The actual nutrient uptake will not increase at high potential nutrient supply level, where it may be limited by other nutrients. Thus the actual nutrient uptake here is calculated as a function of the potential supplies of the other two nutrients. The minimum value of each pair of results is considered as the final actual nutrient uptake; (3) attain the yield ranges of each nutrient from the actual nutrient uptakes estimated in Step 2 at the maximum accumulation (where the nutrient is not limiting) and maximum dilution condition

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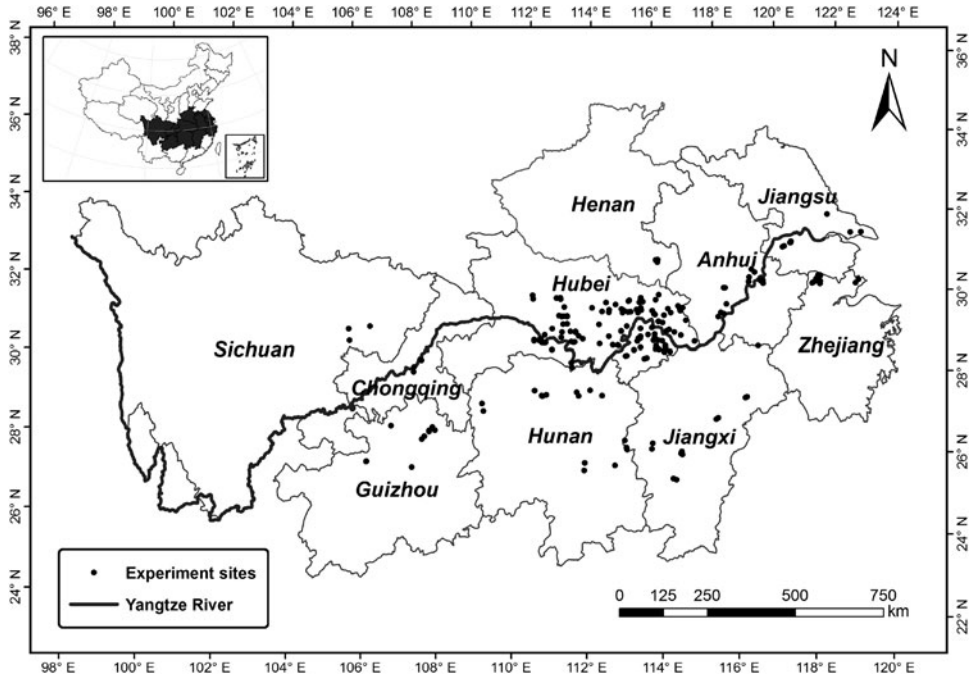


Fig. 1. Distribution of experimental sites around Yangtze River Basin.

Table 1. *Soil properties of the experimental sites around the Yangtze River Basin in China*

Parameter	Unit	Mean	S.E.	Minimum	25% Q	Median	75% Q	Maximum
Soil organic matter	g/kg	28·6	0·67	8·2	21·6	28·3	35·2	57·4
Total N	g/kg	1·52	0·038	0·36	1·06	1·54	1·83	3·38
Available N*	mg/kg	120	2·8	37	93	119	144	251
Olsen-P	mg/kg	18·2	0·74	1·9	11·3	16·0	21·1	56·8
NH_4OAc-K	mg/kg	104	4·0	20	63	92	125	320
Available B†	mg/kg	0·39	0·014	0·09	0·27	0·34	0·49	1·36
pH		6·35	0·068	4·56	5·60	6·30	7·10	8·29

* Available N is alkaline-hydrolysable N

† Available B is hot water B

(where the nutrient is yield limiting); (4) estimate the yield for each possible pair of nutrients using the yield ranges defined in Step 3, then obtain the actual yield from the mean of these six yield estimates; (5) simulate curves of optimum nutrient requirement of N, P and K using a linear–parabolic–plateau curve at the different maximum yield levels. Based on the previous studies (Witt *et al.* 1999; Setiyono *et al.* 2010), a spreadsheet version of the QUEFTS model (using Microsoft Excel 2003 for solver module) was used to calculate the optimal nutrient uptake at the different yield potentials. More detailed information about the QUEFTS model can be found in Janssen *et al.* (1990) and Witt *et al.* (1999).

Critical definitions and calculations

Internal efficiency (IE) of N, P and K represent kg seed yield produced per kg N, P and K taken up by crop; reciprocal internal efficiency (RIE) of N, P and K are the crop N, P and K uptake per 1000 kg seed. They are estimated as follows:

$$IE_{N/P/K} = \frac{Y_{trt}}{N_{trt}}$$

$$RIE_{N/P/K} = \frac{N_{trt}}{Y_{trt}} \times 1000$$

where N_{trt} is nutrient uptake of the treatment and Y_{trt} is seed yield of the treatment. The IE, RIE, N_{trt}, and Y_{trt} are

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expressed in kg/kg, kg/kg, kg/ha and kg/ha, respectively.

Fertilizer recovery efficiency (RE) is estimated as follows:

$$RE_{N/P/K} = \frac{N_{OPT} - N_0}{F_{OPT}} \times 100$$

where N_{OPT} is nutrient uptake of shoots in the OPT treatment; N_0 is nutrient uptake by shoots in the 0-N, 0-P and 0-K treatments, respectively and F_{OPT} is mineral fertilizer application rate of the OPT treatment; RE, N and F are expressed in %, kg/ha and kg/ha, respectively.

The value of maximum accumulation (*a*) of nutrient in the plants represents the maximum accumulation situation of this nutrient when the nutrient supply is sufficient; it is equivalent to the minimum internal efficiency. The value of maximum dilution (*d*) is the maximum dilution situation of this nutrient where the nutrient is yield limiting and it is equivalent to the maximum internal efficiency. Based on previous studies (Witt *et al*. 1999; Zhang *et al*. 2012), the values of *a* and *d* of nutrients in the plants are usually defined as the 2·5th and 97·5th percentiles of the calculated internal efficiencies of a nutrient.

The average seed yield of winter oilseed rape in China in 2011 was 1827 kg/ha, varying from 150 to 2645 kg/ha (National Bureau of Statistics of China 2012); in the current observations the highest yield was 4732 kg/ha. Thus the maximum seed yield was set as 5000 kg/ha. Other potential yield levels, including 2000, 3000 and 4000 kg/ha were also set to predict balanced nutrient requirement for N, P and K.

Model validation

The data source comprised 170 sites where four treatments (NPK, 0-N, 0-P and 0-K) were included. Depending on the five steps mentioned above, crop nutrient uptake at these 170 sites was predicted with the QUEFTS model. The plant-available soil nutrient supplies of each field were measured according to the nutrient omission plots and the potential yield was set depending on the record of high yields at each site. For the rest of the critical parameters, such as fertilizer recovery efficiencies, internal efficiencies and the boundary lines of *a* and *d*, average values for winter oilseed rape were adopted. Then the performance of the QUEFTS model was evaluated through comparisons between predicted and observed values for each specific condition. The root mean square error (RMSE), normalized RMSE (n-RMSE) and index of agreement (IOA), calculated from the following equations, were used to evaluate the performance of the model:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n}}$$

$$NormalizedRMSE = \frac{RMSE}{\bar{O}}$$

$$IOA = 1 - \frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} \left[\left|(P_i - \bar{O})\right| + \left|O_i - \bar{O}\right|\right]^2}$$

where P_i is a predicted value, O_i is an observed value, n is the number of data points and $\bar{O}$ is the mean of the observed values. The RMSE is usually used to assess the mean deviation between simulated and observed values for the same unit. The *n*-RMSE eliminates the unit and can be used for comparison among values with different units. The IOA is a non-dimensional index in the range (0, 1) used for comparisons between simulated value and observed values (Tabi *et al*. 2008). If the IOA is <0·50, then the model's performance is considered to be poor.

RESULTS

Seed yield and nutrient uptake

Across all 1035 on-farm observations, the average seed yield was 1841 kg/ha (Table 2). The high variability in seed yield (which ranged from 28 to 4732 kg/ha) reflected the wide range of environment, soil type and farmers' crop management practices, including imbalanced fertilization, in the Yangtze River Basin. The average seed yield was 2425 kg/ha (range 444–4732 kg/ha), 1298 kg/ha (range 28–3062 kg/ha), 1813 kg/ha (range 130–3827 kg/ha), 2102 kg/ha (range 310–4087 kg/ha), 1955 kg/ha (range 142–4557 kg/ha) and 1005 kg/ha (range 50–2562 kg/ha) for the OPT, 0-N, 0-P, 0-K, FFP and CK treatment, respectively. Lower rapeseed yields were consistently observed in the CK and nutrient omission plots. The total above-ground DM ranged from 105 to 17 324 kg/ha, with an average of 6177 kg/ha. The average HI was 0·29 kg/kg, varying from 0·06 to 0·40 kg/kg. Most of the HI values varied from 0·20 to 0·40; however, 0·048 of the observations had HI values below 0·20 and corresponding yields of <1000 kg/ha (Fig. 2).

In addition to the high variability in seed yield, the total above-ground nutrient accumulation varied

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Table 2. *Seed yield, total above-ground plant DM; HI; plant N, P and K accumulation in seeds, stems, pod walls and above-ground plant DM; and nutrient HI (kg nutrient in seeds per kg nutrient in above-ground plant DM) at maturity of winter oilseed rape in the Yangtze River Basin in China (n = 1035) between 2005 and 2010*

Parameter	Unit	Mean	S.E.	Minimum	25% Q	Median	75% Q	Maximum
Seed yield	kg/ha	1813	26·9	28	1158	1820	2437	4732
Total DM	kg/ha	6177	89·3	105	4030	6145	8102	17324
HI	kg/kg	0·29	0·0014	0·060	0·27	0·30	0·32	0·40
Seed N	kg/ha	64·3	1·02	0·8	38·2	64·3	87·7	160·2
Stem N	kg/ha	15·7	0·39	0·2	7·6	13·4	20·1	154·7
Pod wall N	kg/ha	11·9	0·31	0·1	5·4	9·6	15·1	117·2
Total N	kg/ha	91·9	1·51	1·1	53·9	91·5	123·9	319·6
NHI	kg/kg	0·71	0·0031	0·24	0·67	0·74	0·78	0·86
Seed P	kg/ha	12·5	0·20	0·2	7·8	12·5	16·8	34·6
Stem P	kg/ha	1·9	0·059	0·1	0·8	1·3	2·3	17·4
Pod wall P	kg/ha	2·0	0·048	0·1	0·8	1·6	2·6	12·8
Total P	kg/ha	16·4	0·26	0·3	10·5	15·9	21·8	47·9
PHI	kg/kg	0·77	0·0037	0·25	0·72	0·80	0·85	0·98
Seed K	kg/ha	13·7	0·23	0·2	8·0	13·5	18·7	39·9
Stem K	kg/ha	61·6	1·22	1·4	30·6	55·3	86·2	262·4
Pod wall K	kg/ha	41·5	0·69	0·7	25·2	39·4	54·9	154·7
Total K	kg/ha	116·8	1·92	2·3	69·0	110·9	158·8	349·6
KHI	kg/kg	0·12	0·0014	0·026	0·10	0·12	0·14	0·51

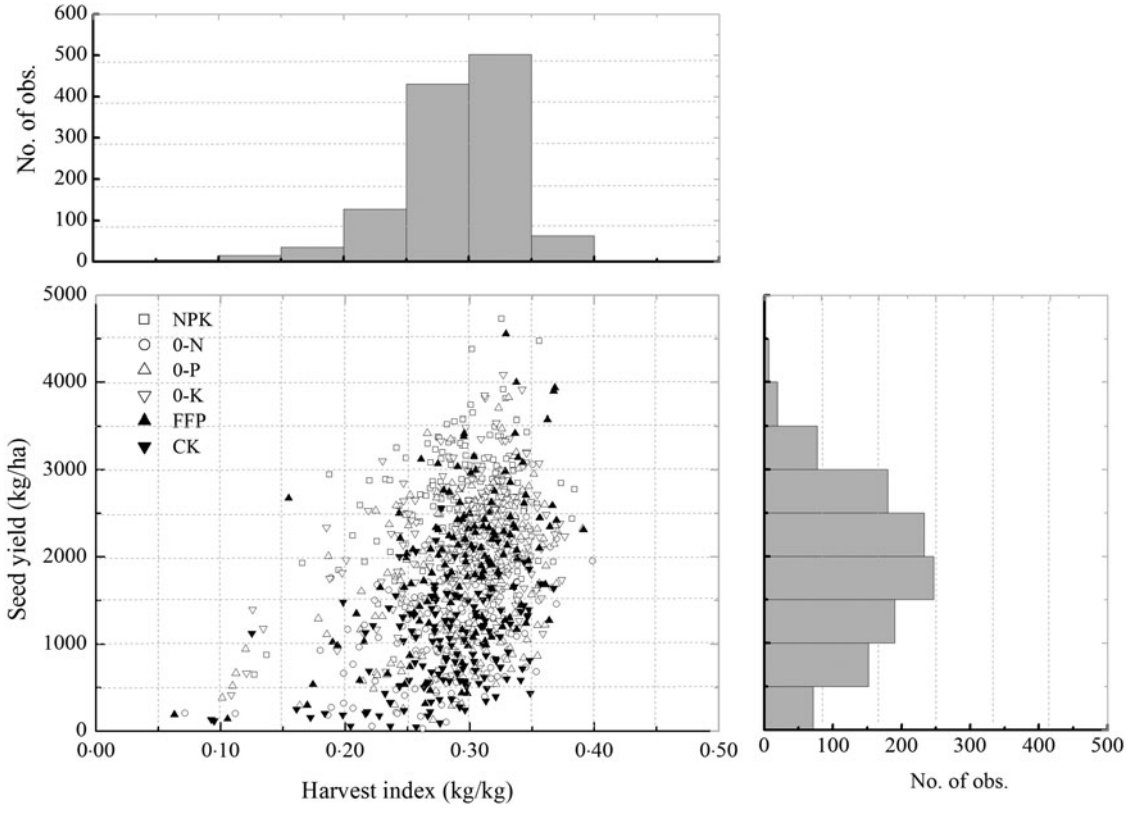


Fig. 2. The relationship between harvest index and seed yield for winter oilseed rape. The data were obtained from farmers' field experiments conducted in the Yangtze River Basin between 2005 and 2010 ($n = 1035$).

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Table 3. *Internal efficiency (IE, kg seed per kg nutrient in above-ground DM), and reciprocal IE (RIE, kg nutrient in above-ground plant DM per 1000 kg seed) for N, P and K at maturity of winter oilseed rape in fields with different fertilizer practices in the* Yangtze River Basin, 2005–2010

Parameter	Unit	*n*	Mean	S.E.	Minimum	25% Q	Median	75% Q	Maximum
Nitrogen (N)									
IE, 0-N plots	kg/kg	174	23·8	0·38	8·3	20·4	23·6	27·2	35·8
IE, NPK	kg/kg	211	20·2	0·30	8·2	17·1	20·0	22·9	31·5
IE, FFP	kg/kg	140	20·3	0·40	5·5	17·5	20·8	23·5	32·7
IE, all plots	kg/kg	1035	20·9	0·16	5·5	17·6	20·9	24·2	36·5
RIE, 0-N plots	kg/t	174	44·1	0·87	27·9	36·8	42·3	49·0	120·1
RIE, NPK	kg/t	211	52·3	0·91	31·7	43·6	50·1	58·6	122·0
RIE, FFP	kg/t	140	53	1·6	31	43	48	57	182
RIE, all plots	kg/t	1035	51·3	0·51	27·4	41·3	47·8	56·9	182·3
Phosphorus (P)									
IE, 0-P plots	kg/kg	185	136·4	3·2	43·5	110·1	130·3	160·5	267·4
IE, NPK	kg/kg	211	113·1	1·9	39·7	95·5	114·8	128·9	182·0
IE, FFP	kg/kg	140	119·4	3·0	21·7	95·8	116·9	142·9	222·5
IE, all plots	kg/kg	1035	116·5	1·1	21·7	93·4	113·6	132·4	267·4
RIE, 0-P plots	kg/t	185	8·2	0·22	3·7	6·2	7·7	9·1	23·0
RIE, NPK	kg/t	211	9·5	0·20	5·5	7·8	8·7	10·5	25·2
RIE, FFP	kg/t	140	9·5	0·40	4·5	7·0	8·6	10·4	46·2
RIE, all plots	kg/t	1035	9·5	0·11	3·7	7·6	8·8	10·7	46·2
Potassium (K)									
IE, 0-K plots	kg/kg	186	20·1	0·70	4·0	14·8	18·4	23·2	70·0
IE, NPK	kg/kg	211	16·0	0·33	4·1	13·0	15·3	18·3	36·3
IE, FFP	kg/kg	140	17·6	0·56	1·9	14·5	16·3	20·0	48·1
IE, all plots	kg/kg	1035	16·7	0·20	1·9	13·2	16·0	18·9	70·0
RIE, 0-K plots	kg/t	186	60	2·2	14	43	54	68	249
RIE, NPK	kg/t	211	69	1·8	28	55	65	77	242
RIE, FFP	kg/t	140	68	4·1	21	50	61	69	519
RIE, all plots	kg/t	1035	69	1·1	14	53	63	76	519

tremendously in the seeds, pod walls and stems. On average, the total accumulated N, P and K amounts were 91·9 kg N/ha, 16·4 kg P/ha and 116·8 kg K/ha, resulting in a yield of 1813 kg/ha or an N: P: K ratio of 5·6:1·0:7·1 in the plant DM. Approximately 0·70 of the N and 0·77 of the P in the above-ground DM was distributed in the seeds, whereas only 0·12 of the K was stored in the seeds. The N, P and K nutrient harvest indices (the nutrient accumulation in the seeds as a proportion of the nutrient accumulation in the above-ground plant DM) were 0·71, 0·77 and 0·12 kg/kg, respectively.

Internal efficiency, plant available soil nutrient supply and nutrient recovery efficiency

As expected, IE varied widely, from 5·5 to 36·5 kg seed/kg of N taken up by crop, from 21·7 to 267·4 seed/kg of P taken up by crop, and from 1·9 to 70·0 seed/kg of K taken up by crop. The average IEs across all sites and seasons were 20·9 kg seed/kg N, 116·5 kg seed/kg P and 16·7 kg seed/kg K, equivalent to reciprocal internal nutrient efficiencies (RIEs) of 51·3 kg N, 9·5 kg P and 68·5 kg K/1000 kg seed (Table 3). Values of 23·8 kg seed/kg N, 136·4 kg seed/kg P and 20·1 kg seed/kg K were obtained in the present study for the 0-N, 0-P and 0-K plots, respectively. These values were higher than those obtained for the FFP and OPT plots. The internal N efficiency values were similar for OPT and FFP plots because of the comparable seed yields and N fertilizer input levels. Nevertheless, the internal P and K efficiency values were slightly lower for the OPT treatment than for the FFP treatment, which might be related to the lower P and K fertilizer input levels for the FFP plots.

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Table 4. *Descriptive statistics of the data sets used for the QUEFTS model to describe the relationship between seed yield and nutrient uptake for winter oilseed rape around the* Yangtze River Basin, 2005–2010

Parameter	*n*	Mean	S.E.	Minimum	25% Q	Median	75% Q	Maximum
Indigenous soil nutrient supply (kg/ha)								
N	174	57	2·3	1	31	56	77	142
P	185	14·6	0·56	0·6	8·5	14·6	19·2	39·2
K	186	120	4·0	18	74	115	161	271
Fertilizer recovery efficiency (%)								
N	174	36	1·3	0·1	24	34	46	102
P	185	20	1·1	−18	9	18	27	69
K	186	43	2·4	−36	20	40	58	162

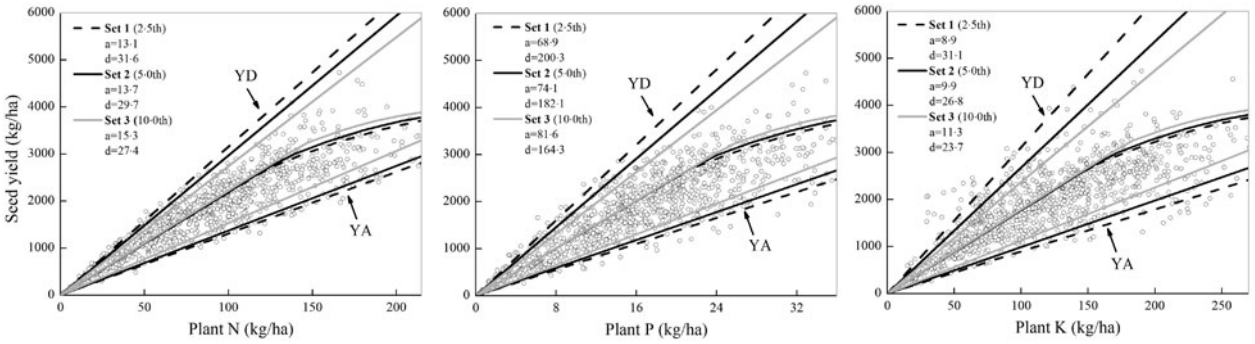


Fig. 3. The relationship between seed yield and total above-ground N, P and K uptake of winter oilseed rape at different data sets of *a* and *d* values, by excluding the upper and lower 2·5th (set 1), 5·0th (set 2) and 10·0th (set 3) percentiles of the internal efficiencies for all nutrient when HI ≥ 0·20. The balanced N, P and K uptake requirements (YN, YP and YK) for a yield potential of 4000 kg/ha were calculated using the QUEFTS model based on the different boundary lines. The regression lines on the left side of each figure represent the boundary of maximum dilution (YD), and the lines on the right indicate the boundary of maximum accumulation (YA).

The plant-available soil N supply ranged from 1·1 to 142·0 kg N/ha, with an average of 57·3 kg N/ha, the plant available soil P supply ranged from 0·6 to 39·2 kg P/ha, with an average of 14·6 kg P/ha and the plant available soil K supply ranged from 17·8 to 270·5 kg K/ha, with an average of 119·8 kg K/ha. The average fertilizer recovery efficiencies for optimal fertilization were 0·36, 0·20 and 0·43 for N, P and K, respectively (Table 4).

Selection of data for adjusting the Quantitative Evaluation of the Fertility of Tropical Soils to oilseed rape

The aim of using the QUEFTS model was to determine the boundary lines of maximum accumulation (*a*) and maximum dilution (*d*) of nutrients in winter oilseed rape. On the basis of previous studies (Witt *et al*. 1999; Zhang *et al*. 2012), the 2·5th and 97·5th percentiles of the calculated IEs of a nutrient were defined as the values of *a* and *d*. In addition, to test the feasibility of this dataset on rapeseed, another two datasets for the model were estimated by excluding the upper and lower 0·05 (Set II) and 0·10 (Set III) of all IEs as outliers when HI > 0·20. The simulated nutrient requirements of winter oilseed rape with different envelope coefficients are shown in Fig. 3. The envelopes were largely influenced by the different data sets and the envelopes were narrowest excluding 10th percentiles of IEs. However, the optimal nutrient requirements simulated by the QUEFTS model were similar for all three sets. It should be noticed that when the target yield approached the yield potential, calculated nutrient uptake under different datasets was different. For example, nutrient uptakes were 167·4 kg N/ha, 29·4 kg P/ha and 208·1 kg K/ha for a target yield of 3·5 t/ha on constants of Set III, which were 10·1–11·4% lower compared with the values for Set I (exclusion of 2·5th and 97·5th percentiles). Considering the maximum range of variability in

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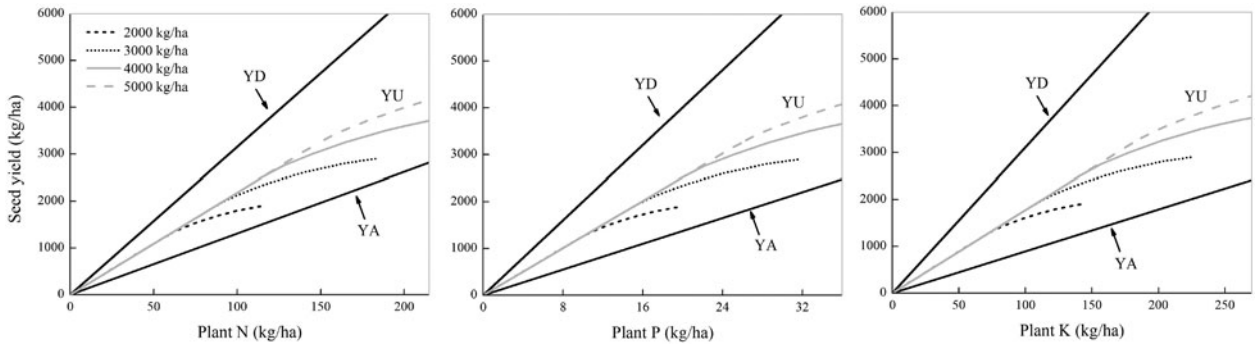


Fig. 4. Balanced nutrient requirement for N, P and K at different yield potentials simulated by the QUEFTS model. YD, YA and YU represent the maximum dilution, maximum accumulation and optimal nutrient uptake of N, P and K, which are calculated by the QUEFTS model from excluding the upper and lower 2·5th percentiles of the internal efficiencies for all nutrients when HI ≥ 0·20.

Set 1, it was used to define the values of maximum accumulation and maximum dilution of each nutrient in winter oilseed rape. After excluding observations with HI values <0·20, the nutrient uptake coefficients for winter oilseed rape were found to be *a*N = 13·1, *d*N = 31·6, *a*P = 68·9, *d*P = 200·3, *a*K = 8·9 and *d*K = 31·1. The ratios of maximum dilution to maximum accumulation (*d*/*a*) were 2·4, 2·9 and 3·5 for N, P and K, respectively, indicating that N was more important for rapeseed yield than P and K.

Estimating the optimal nutrient uptake by the potential yield

The potential yield influenced the optimal nutrient requirement to achieve a specific target yield. Depending on season and site, the seed yield in Yangtze River Basin ranged from 28–4732 kg/ha. The optimal nutrient requirement at the different potential yields is shown in Fig. 4. Regardless of the yield potential, the crop nutrient uptake increased linearly with seed yield at lower yield levels (<0·60–0·70 of potential yield). The IEs calculated from the model were 21·8 kg seed/kg N, 125·0 kg seed/kg P and 17·5 kg seed/kg K, indicating that 45·9 kg N, 8·0 kg P and 57·0 kg K would be needed to produce a 1000-kg seed yield. When the target yields approached the yield potential, the IEs decrease gradually.

Preliminary validation of the model

The crop nutrient uptakes simulated with the QUEFTS model using the standard coefficient obtained from analysis of the data presented in the present paper and the specific parameters of each field (plant available soil nutrient supply) compared well with the observed values (Fig. 5). The RMSE values were 29·8, 6·3 and 51·4 kg/ha for N, P and K, respectively, the n-RMSE values were 24·6, 28·9 and 32·8 for N, P and K, respectively, and the IOA values were 0·86, 0·80 and 0·77 for N, P and K, respectively. All the values indicate good performance of the model and that there were no discrepancies between simulated and observed data. These results confirm that the QUEFTS model can be used to predict the nutrient uptake of winter oilseed rape on the basis of specific field conditions.

DISCUSSION

Determination of the boundary lines of maximum accumulation (a) and maximum dilution (d) of nutrients was one of the most critical parameters in the generation of the winter oilseed rape model. The maximum accumulation and maximum dilution of nutrients were not only influenced by variety, weather conditions, soil type, etc., but also affected by nutrient management (Witt *et al*. 1999; Zhang *et al*. 2012). The high variability in seed yield revealed in the present study reflected exactly the wide ranges of environments, soil conditions and fertilizer management practices, which provided a robust database for assessing the internal nutrient efficiencies of winter oilseed rape. The average reciprocal internal nutrient efficiencies across all sites and seasons were 51·3 kg N, 9·5 kg P and 68·5 kg K/1000 kg seed. These values were comparable to those reported in previous studies conducted in the Yangtze River Basin in China (Xu *et al*. 2012; Yang *et al*. 2012). However, the values were lower than those reported in Europe. Barraclough (1989) reported oilseed rape nutrient

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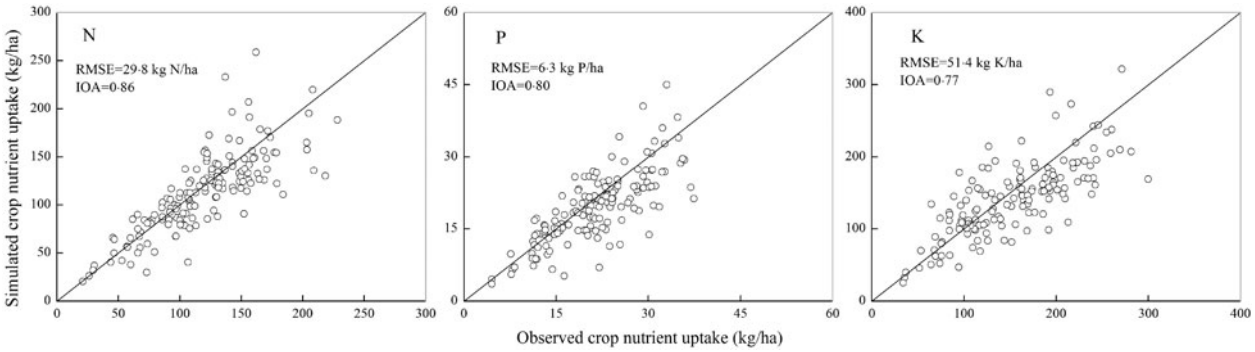


Fig. 5. The relationship between observed and simulated N, P and K uptake in above-ground plant DM for winter oilseed rape.

uptake amounts of 67·4 kg N, 8·0 kg P and 57·0 kg K/1000 kg seed at a yield of 5·4 t/ha. Orlovius (2003) showed that the nutrient requirements for a seed yield of 3·5 t/ha were 57·4–85·7 kg N, 11·4–16·2 kg P and 83·3–107·1 kg K/1000 kg seed.

A prerequisite for using the database was a dataset where crop growth was not subjected to limitations other than in N, P or K supply (Janssen *et al*. 1990). However, in field conditions other stresses such as pests, diseases and environmental stress cannot be avoided, which would influence seed yield (Zhou *et al*. 1999). Not all data in the database met the requirements of the model. The HI served as an efficient tool for selecting data to use for calibration of the model, because it was likely that a lower HI would be associated with pest, disease and environmental stress (Hay 1995). The HI of oilseed rape usually ranged from 0·25 to 0·50 kg/kg (Hühn *et al*. 1991; Diepenbrock 2000; Rathke *et al*. 2005; Kessel *et al*. 2012). In the database used in the present study, the HI varied from 0·06 to 0·40 kg/kg, with an average of 0·29 kg/kg. The data with lower HI and seed yield were associated with limitations other than in N, P or K supply. The corresponding yield with lower HI (<0·20) in the current experiments was <1000 kg/ha and the data should be excluded. When the data with a HI < 0·20 were excluded from model testing, the average of most parameters such as seed yield, nutrient uptake and internal nutrient efficiencies was not influenced, owing to the large number of observations ($n = 990$). Thus, the HI of 0·20 was selected as a threshold value for excluding data from the calibration of QUEFTS model.

According to previous studies in rice, wheat and maize (Witt *et al*. 1999; Liu *et al*. 2006; Zhang *et al*. 2012), the boundary lines of maximum accumulation (a) and the maximum dilution (d) of nutrients were the 2·5th and 97·5th percentiles of the calculated internal efficiency of a nutrient. From the sensitivity test of different datasets excluding the upper and lower 2·5, 5·0 and 10·0 percentiles of all IE data, similar results were noticed in winter oilseed rape. Considering the maximum range of variability, the 2·5th and 97·5th percentiles of the calculated IE were considered as the a and d coefficients. The nutrient uptake coefficients for winter oilseed rape were aN = 13·1, dN = 31·3, aP = 69·0, dP = 196·5, aK = 8·9 and dK = 30·2 after excluding observations with HI < 0·20. Apparently, the IEs of oilseed rape were lower than rice, wheat and maize (Witt *et al*. 1999; Zhang *et al*. 2012; Chuan *et al*. 2013), which suggests that the nutrient requirements of winter oilseed rape were greater than those of these other crops (Brennan & Bolland 2009).

On the basis of the data settings, the calculated above-ground nutrient uptakes were 91·7 kg N/ha, 15·9 kg P/ha and 112·7 kg/K ha for a target yield of 2000 kg/ha. These calculated values were close to the measured values (Table 2), which confirmed that the QUEFTS model could be used to predict the nutrient uptake of winter oilseed rape. In 0-N plots, most of the dataset was above the balanced N uptake line and close to the upper boundary, indicating that N supplied by the soil was insufficient for oilseed rape production in the Yangtze River Basin. This was consistent with the finding of many previous studies that N supply was the predominant limiting factor in rapeseed yield (Wang *et al*. 2010, 2012). For optimal fertilization, most of the N uptake data were close to the optimal lines predicted by the model, meaning that the N application levels were reasonable. In contrast to N, P and K had scattered uptake distributions,

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even for the 0-P, 0-K and OPT plots. The data below the optimal lines and close to the lower boundary for the OPT plots showed that the P and K application levels were excessive. In the present studies, fertilization at the optimal rates (180 kg N/ha, 90 kg P_2O_5/ha and 120 kg K_2O/ha) could have increased seed yield considerably, by 29·1% on average, over that achieved by the farmers' fertilization practices (Zou 2010). However, in 0·28 of the experiments, only slightly improved seed yield responses to the recommended fertilization rates were observed, in comparison to the yields achieved with the current FFP. These findings suggest that, depending on the regional mean optimal fertilization rates, refining the recommended fertilization rates on the basis of information on specific local conditions will be important to improve seed yield and fertilizer use efficiency considerably.

The predicted values simulated by QUEFTS model compared well with observed values under specific conditions, indicating that the QUEFTS model could be used to predict the nutrient requirement of winter oilseed rape on the basis of specific field conditions. Nevertheless, it cannot be ignored that the QUEFTS model had been developed to work in conditions when crop growth was not affected by other factors such as water limitation, waterlogging, restricted root penetration and poor crop management (Janssen *et al*. 1990; Smaling & Janssen 1993). Under rainfed conditions, oilseed rape nutrient uptake depends heavily on rainfall during the growing season; therefore this approach might not be optimal because yield response to fertilizer would be highly variable from year to year. In addition to the temporal variability of yield response, there was a spatial variability of yield response which made it hard to implement the model for a whole farm, or a region relying on this approach alone. Thus, combining the QUEFTS model with other crop simulation models, such as the WOrld FOod Studies (WOFOST) model (van Diepen *et al*. 1989) and the Crop Environment REsource Synthesis (CERES) model (Gabrielle *et al*. 1998), would be helpful for accurate assessments of crop nutrient requirements and optimizing the fertilizer recommendation system for specific conditions/environments. Based on the determination of the crop's optimal nutrient requirements predicted by the QUEFTS model, a Nutrient Expert system has been developed by the International Plant Nutrition Institute (IPNI), which provides site-specific fertilizer recommendations for farmers to achieve higher yield and profits, and has been used in Indonesia, the Philippines and China (Pampolino *et al*. 2012). Also, in some oilseed rape growing areas of the world, precision agricultural management is becoming economically sound and available to farmers. Precision farming systems could use the QUEFTS model to predict spatial variation in crop nutrient requirement based on soil chemical characteristics and make fertilizer recommendations; then, considering the temporal and spatial variability of crop nutrient uptake and soil nutrient supply, real-time monitoring via plant analysis (Thoren & Schmidhalter 2009) or soil available nutrient content testing (Sims *et al*. 2002; Cui *et al*. 2008) might provide a more timely reflection of the crop nutrient demand and guide the fertilizer recommendation under each specific condition. In summary, the combined use of the QUEFTS model and other crop simulation models or soil/plant rapid-test technologies for assessing specific field conditions will be effective for achieving high yields and high nutrient use efficiencies of winter oilseed rape.

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REFERENCES

Barraclough, P. B. (1989). Root growth, macro-nutrient uptake dynamics and soil fertility requirements of a high-yielding winter oilseed rape crop. *Plant and Soil* **119**, 59–70.

BBCH (Biologische Bundesanstallt für Land-und Forstwirtschaft) (1997). *Growth Stages of Mono-and Dicotyledonous Plants: BBCH Monograph*. Berlin: Blackwell Wissenschafts-Verlag.

Berry, P. M., Spink, J., Foulkes, M. J. & White, P. J. (2010). The physiological basis of genotypic differences in nitrogen use efficiency in oilseed rape (*Brassica napus* L.). *Field Crops Research* **119**, 365–373.

Brennan, R. F. & Bolland, M. D. A. (2007*a*). Effect of fertiliser phosphorus and nitrogen on the concentrations of oil and protein in grain and the grain yield of canola (*Brassica napus* L.) grown in south-western Australia. *Australian Journal of Experimental Agriculture* **47**, 984–991.

https://doi.org/10.1017/S0021859615000301 Published online by Cambridge University Press

Brennan, R. F. & Bolland, M. D. A. (2007*b*). Influence of potassium and nitrogen fertilizer on yield, oil and protein concentration of canola (*Brassica napus* L.) grain harvested in south-western Australia. *Australian Journal of Experimental Agriculture* **47**, 976–983.

Brennan, R. F. & Bolland, M. D. A. (2009). Comparing the nitrogen and potassium requirements of canola and wheat for yield and grain quality. *Journal of Plant Nutrition* **32**, 2008–2026.

Chen, X. P., Cui, Z. L., Vitousek, P. M., Cassman, K. G., Matson, P. A., Bai, J. S., Meng, Q. F., Hou, P., Yue, S. C., Romheld, V. & Zhang, F. S. (2011). Integrated soil-crop system management for food security. *Proceedings of the National Academy of Sciences of the United States of America* **108**, 6399–6404.

Chuan, L., He, P., Jin, J., Li, S., Grant, C., Xu, X., Qiu, S., Zhao, S. & Zhou, W. (2013). Estimating nutrient uptake requirements for wheat in China. *Field Crops Research* **146**, 96–104.

Cui, Z. L., Chen, X. P., Miao, Y. X., Zhang, F. S., Sun, Q. P., Schroder, J., Zhang, H. L., Li, J. L., Shi, L. W., Xu, J. F., Ye, Y. L., Liu, C. S., Yang, Z. P., Zhang, Q., Huang, S. M. & Bao, D. J. (2008). On-farm evaluation of the improved soil N_{min}-based nitrogen management for summer maize in North China Plain. *Agronomy Journal* **100**, 517–525.

Diepenbrock, W. (2000). Yield analysis of winter oilseed rape (*Brassica napus* L.): a review. *Field Crops Research* **67**, 35–49.

Fismes, J., Vong, P. C., Guckert, A. & Frossard, E. (2000). Influence of sulfur on apparent N-use efficiency, yield and quality of oilseed rape (*Brassica napus* L.) grown on a calcareous soil. *European Journal of Agronomy* **12**, 127–141.

Gabrielle, B., Denoroy, P., Gosse, G., Justes, E. & Andersen, M. N. (1998). Development and evaluation of a CERES-type model for winter oilseed rape. *Field Crops Research* **57**, 95–111.

Guo, J. H., Liu, X. J., Zhang, Y., Shen, J. L., Han, W. X., Zhang, W. F., Christie, P., Goulding, K. W. T., Vitousek, P. M. & Zhang, F. S. (2010). Significant acidification in major Chinese croplands. *Science* **327**, 1008–1010.

Hay, R. K. M. (1995). Harvest index: a review of its use in plant breeding and crop physiology. *Annals of Applied Biology* **126**, 197–216.

Hossain, M. & Singh, V. P. (2000). Fertilizer use in Asian agriculture: implications for sustaining food security and the environment. *Nutrient Cycling in Agroecosystems* **57**, 155–169.

Hühn, M., Grosse, F. & Leon, J. (1991). On harvest indices of winter oilseed rape (*Brassica nupus* L.). *Journal of Agronomy and Crop Science* **167**, 299–309.

Janssen, B. H., Guiking, F. C. T., Van Der Eijk, D., Smaling, E. M. A., Wolf, J. & Van Reuler, H. (1990). A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). *Geoderma* **46**, 299–318.

Ju, X. T., Kou, C. L., Zhang, F. S. & Christie, P. (2006). Nitrogen balance and groundwater nitrate contamination: comparison among three intensive cropping systems on the North China Plain. *Environmental Pollution* **143**, 117–125.

Kessel, B., Schierholt, A. & Becker, H. C. (2012). Nitrogen use efficiency in a genetically diverse set of winter oilseed rape (*Brassica nupus* L.). *Crop Science* **52**, 2546–2554.

Liu, M., Yu, Z., Liu, Y. & Konijn, N. T. (2006). Fertilizer requirements for wheat and maize in China: the QUEFTS approach. *Nutrient Cycling in Agroecosystems* **74**, 245–258.

National Bureau Of Statistics Of China. (2012). *China Statistical Yearbook*. Beijing: China Statistics Press.

Orlovius, K. (2003). *Fertilizing for High Yield and Quality: Oilseed Rape*. IPI Bulletin No. 16. Basel, Switzerland: International Potash Research Institute.

Ozer, H. (2003). Sowing date and nitrogen rate effects on growth, yield and yield components of two summer rapeseed cultivars. *European Journal of Agronomy* **19**, 453–463.

Pampolino, M. F., Witt, C., Pasuquin, J. M., Johnston, A. & Fisher, M. (2012). Development approach and evaluation of the nutrient expert software for nutrient management in cereal crops. *Computers and Electronics in Agriculture* **88**, 103–110.

Rathke, G. W., Christen, O. & Diepenbrock, W. (2005). Effects of nitrogen source and rate on productivity and quality of winter oilseed rape (*Brassica napus* L.) grown in different crop rotations. *Field Crops Research* **94**, 103–113.

Ren, T., Lu, J., Li, H., Zou, J., Xu, H., Liu, X. & Li, X. (2013). Potassium-fertilizer management in winter oilseed-rape production in China. *Journal of Plant Nutrition and Soil Science* **176**, 429–440.

Rondanini, D. P., Gomez, N. V., Agosti, M. B. & Miralles, D. J. (2012). Global trends of rapeseed grain yield stability and rapeseed-to-wheat yield ratio in the last four decades. *European Journal of Agronomy* **37**, 56–65.

Schulte Auf'm Erley, G., Behrens, T., Ulas, A., Wiesler, F. & Horst, W. J. (2011). Agronomic traits contributing to nitrogen efficiency of winter oilseed rape cultivars. *Field Crops Research* **124**, 114–123.

Setiyono, T. D., Walters, D. T., Cassman, K. G., Witt, C. & Dobermann, A. (2010). Estimating maize nutrient uptake requirements. *Field Crops Research* **118**, 158–168.

Sims, J. T., Maguire, R. O., Leytem, A. B., Gartley, K. L. & Pautler, M. C. (2002). Evaluation of Mehlich 3 as an agri-environmental soil phosphorus test for the Mid-Atlantic United States of America. *Soil Science Society of America Journal* **66**, 2016–2032.

Smaling, E. M. A. & Janssen, B. H. (1993). Calibration of QUEFTS, a model predicting nutrient uptake and yields from chemical soil fertility indices. *Geoderma* **59**, 21–44.

Tabi, F. O., Diels, J., Ogunkunle, A. O., Iwuafor, E. N. O., Vanlauwe, B. & Sanginga, N. (2008). Potential nutrient supply, nutrient utilization efficiencies, fertilizer recovery rates and maize yield in northern Nigeria. *Nutrient Cycling in Agroecosystems* **80**, 161–172.

Taylor, A. J., Smith, C. J. & Wilson, I. B. (1991). Effect of irrigation and nitrogen fertilizer on yield, oil content, nitrogen accumulation and water use of canola (*Brassica napus* L.). *Fertilizer Research* **29**, 249–260.

Thomas, R. L., Sheard, R. W. & Moyer, J. R. (1967). Comparison of conventional and automated procedures for nitrogen, phosphorus, and potassium analysis of

https://doi.org/10.1017/S0021859615000301 Published online by Cambridge University Press

plant material using a single digestion. *Agronomy Journal* **59**, 240–243.

Thoren, D. & Schmidhalter, U. (2009). Nitrogen status and biomass determination of oilseed rape by laser-induced chlorophyll fluorescence. *European Journal of Agronomy* **30**, 238–242.

Van Diepen, C. A., Wolf, J., Van Keulen & Rappoldt, C. (1989). WOFOST: a simulation model of crop production. *Soil Use and Management* **5**, 16–24.

Vitousek, P. M., Naylor, R., Crews, T., David, M. B., Drinkwater, L. E., Holland, E., Johnes, P. J., Katzenberger, J., Martinelli, L. A., Matson, P. A., Nziguheba, G., Ojima, D., Palm, C. A., Robertson, G. P., Sanchez, P. A., Townsend, A. R. & Zhang, F. S. (2009). Agriculture. Nutrient imbalances in agricultural development. *Science* **324**, 1519–1520.

Wang, G. H., Dobermann, A., Witt, C., Sun, Q. Z. & Fu, R. X. (2001). Performance of site-specific nutrient management for irrigated rice in Southeast China. *Agronomy Journal* **93**, 869–878.

Wang, W. N., Lu, J. W., Li, Y. S., Zou, J., Su, W., Li, X. K. & Li, Y. C. (2010). Study on fertilization effect and fertilizer contribution rate of different crops at present production conditions. *Scientia Agricultura Sinica* **43**, 3997–4007.

Wang, Y. (2014). *Study on the different responses to N, P, and K fertilizers between direct sown and transplanted winter oilseed rape*. Ph.D. Thesis, Huazhong Agricultural University, Wuhan, China.

Wang, Y., Li, X. K., Li, Y. Y., Li, J. F., Xiao, G. B., Zheng, W., Yuan, F. S., Lu, Y. H., Liao, Y. L. & Lu, J. W. (2012). Response of direct-seeding rapeseed to fertilization in fields of red soil different in fertility. *Acta Pedologica Sinica* **49**, 121–129.

Witt, C., Dobermann, A., Abdulrachman, S., Gines, H. C., Wang, G. H., Nagarajan, R., Satawatananont, S., Son, T. T., Tan, P. S., Tiem, L. V., Simbahan, G. C. & Olk, D. C. (1999). Internal nutrient efficiencies of irrigated lowland rice in tropical and subtropical Asia. *Field Crops Research* **63**, 113–138.

Xu, F. T., Gu, H. H. & Xu, J. (2012). Response of rape to N, P and K fertilizer in Haimen II: fertilizing benefits. *Soils* **44**, 237–241.

Yang, Y., Liu, Q., Song, H. X., Guan, C. Y., Rong, X. M. & Peng, J. W. (2012). Effects of different NPK ratios on nutrients absorption, carbon and nitrogen metabolism, and grain yield of rapeseed. *Acta Agriculturae Zhejiangensis* **24**, 99–104.

Zhang, F. S., Chen, X. P. & Chen, Q. (2009). *Fertiliser Recommendations for Major Crops in China*. Beijing: China Agricultural University Press.

Zhang, F. S., Cui, Z., Fan, M., Zhang, W., Chen, X. & Jiang, R. (2011). Integrated soil-crop system management: reducing environmental risk while increasing crop productivity and improving nutrient use efficiency in China. *Journal of Environmental Quality* **40**, 1051–1057.

Zhang, Y., Hou, P., Gao, Q., Chen, X., Zhang, F. & Cui, Z. (2012). On-farm estimation of nutrient requirements for spring corn in North China. *Agronomy Journal* **104**, 1436–1442.

Zhou, Y., Fitt, B. D. L., Welham, S. J., Gladders, P., Sansford, C. E. & West, J. S. (1999). Effects of severity and timing of stem canker (*Leptosphaeria maculans*) symptoms on yield of winter oilseed rape (*Brassica napus*) in the UK. *European Journal of Plant Pathology* **105**, 715–728.

Zou, J. (2010). *Study on response of winter rapeseed to NPKB fertilization and abundance and deficiency indices of soil nutrients*. Ph.D. Thesis, Huazhong Agricultural University, Wuhan, China.

Zou, J., Lu, J. W., Chen, F. & Li, Y. S. (2009). Effect of nitrogen, phosphorus, potassium, and boron fertilizers on yield and profit of rapeseed (*Brassica napus* L.) in the Yangtze River Basin. *Acta Agronomica Sinica* **35**, 87–92.

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