Estimating Nutrient Uptake Requirements for Potatoes Based on QUEFTS Analysis in China

Yaxin Xu, Ping He,* Xinpeng Xu, Shaojun Qiu, Sami Ullah, Qiang Gao, Wei Zhou*

ABSTRACT

Excessive or imbalanced fertilization has not only decreased nutrient use efficiency, but also degraded arable land and posed a great threat to the environment. In this study, the datasets were collected from field experiments for the period 1992 to 2017 in the main potato (*Solanum tuberosum* L.) production regions of China. We used the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model to estimate the soil-plant balanced N, P, and K requirements for the potato in China. Our results revealed that there were great differences in the potato yield and nutrient uptake. The upper and lower 2.5th percentiles of N, P, and K internal efficiencies (IE, kg tuber per kg nutrient in the total plant) data were used as maximum accumulation (*a*) and maximum dilution (*d*) boundary parameters in the QUEFTS model, which were 133 and 463 kg kg^{-1} for N, 652 and 3030 kg kg^{-1} for P, and 119 and 790 kg kg^{-1} for K, respectively. The QUEFTS model predicted plant nutrient uptake of 4.0 kg N, 0.7 kg P, and 3.5 kg K to produce 1 Mg of tuber in the linearly distributed portion, and a corresponding tuber nutrient demand of 2.9 kg N, 0.5 kg P, and 2.3 kg K to produce 1 Mg of tuber. Field validation experiments confirmed that the QUEFTS model could be used to simulate optimum nutrient uptake and provide appropriate parameters in building fertilizer recommendation, which helps improve nutrient use efficiency for potato in China.

Core Ideas

- This is the first report of QUEFTS model on estimating the optimum nutrient requirements for potato crops in China.
- The datasets used in this study were collected from multi-year-site field experiments.
- Multi-site field validation experiments in potato-producing areas confirmed the feasibility of QUEFTS model-simulated nutrient uptake.

Potato plants have relatively shallow root systems and is grown widely in China, ranking fourth of all crop productions. In pursuit of higher yields, farmers are applying tremendous amounts of fertilizers, which has led to not only lower yield, but low nutrient use efficiency and environmental problems as well (Chen et al., 2012; Liu et al., 2014). To better improve nutrient use efficiency and decrease environmental impacts, improved methods for optimum fertilizer recommendations are necessary for potato production in China.

The traditional fertilization recommendation based on soil testing has contributed positive yield responses in potato-producing areas of China (Duan et al., 2014; Li et al., 2015). Although soil testing is a more accurate method to evaluate the nutrient availability in the soil for scientists, there are great challenges in terms of fertilizer application for smallholder farmers and the wide variety of potato cropping systems in China (Alva et al., 2011; Bai, 2015; Cui et al., 2018). Site-specific nutrient management (SSNM) was originally used for rice (Oryza *sativa* L.) and mainly focused on the optimization of site-specific N management based on potential yield and yield response to the application of fertilizer (Dobermann et al., 2002; Pasuquin et al., 2014). A modification of the QUEFTS model has been advocated by SSNM to estimate field-specific N, P, and K recommendations (Smaling and Janssen, 1993; Pampolino et al., 2012; Pasuquin et al., 2014). In the past, many nutrient management strategies have only focused on a single nutrient, ignoring inter-relationships among N, P, and K. The QUEFTS model, however, simulates N, P, and K interactions in soil–plant systems, as well as the balance between the indigenous soil nutrient supply and plant nutrient uptake based on different potential yields (Setiyono et al., 2010).

The QUEFTS model has been used for rice (Xu et al., 2015), wheat (Chuan et al., 2013a, 2013b), soybean [*Glycine max* (L.) Merr.] (Yang et al., 2017), rapeseed (*Brassica napus* L.) (Ren et al., 2015), cassava (*Manihot esculenta* Crantz) (Byju et al., 2016) and sweet potato [*Ipomoea batatas* (L.) Lam.] crops (Kumar et al., 2016) over large areas. Years of field validation have demonstrated that this model is adaptable to different crops, production areas, climates, and soil types, and therefore could possibly

---

Published in Agron. J. 111:1–8 (2019)
doi:10.2134/agronj2018.09.0572
Available freely online through the author-supported open access option

Y. Xu, P. He, X. Xu, S. Qiu, S. Ullah, and W. Zhou, Ministry of Agriculture Key Lab. of Plant Nutrition and Fertilizer, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, PR China; Y. Xu and Q. Gao, College of Resources and Environment, Jilin Agricultural Univ., Changchun, 130124, PR China. Received 10 Sept. 2018. Accepted 26 May 2019. *Corresponding author (heping02@caas.cn, zhouwei02@caas.cn).

Abbreviations: HI, harvest index; IE, internal efficiency; IPNI, International Plant Nutrition Institute; QUEFTS, Quantitative Evaluation of the Fertility of Tropical Soils; RIE, reciprocal internal efficiency; SSNM, site-specific nutrient management.

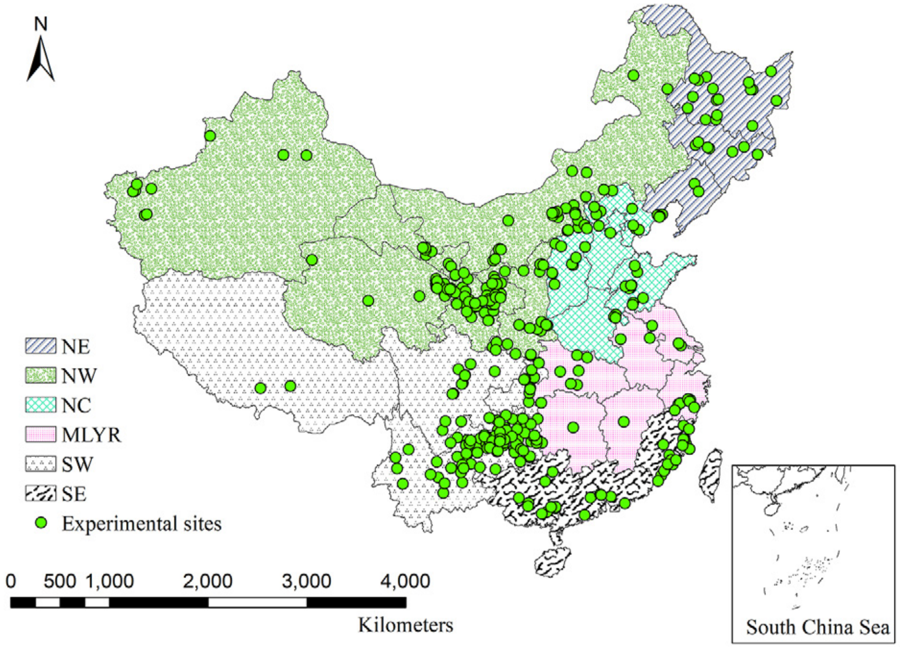

Fig. 1. Distribution of experimental sites in different potato-producing regions of China.

be used to estimate potato nutrient demands for potential yields in China (Sattari et al., 2014)**.** The purposes of the present study were to: (i) determine the relationship between potato nutrient uptake and yield; (ii) estimate the optimal N, P, and K requirements for potato crops; and (iii) evaluate the QUEFTS model-simulated nutrient uptakes using field validation.

MATERIALS AND METHODS

Data Sites

Based on cultivated regions and administrative divisions, six distinct potato-producing areas were divided in China (Teng et al., 1989; Li and Jin, 2011): the Northeast (NE), Northwest (NW), north-central (NC), the Middle and lower reaches of Yangtze River (MLYR), Southeast (SE), and Southwest (SW) (Fig. 1, Table 1). The NE and NW regions use a monocropping system in which potato is planted in late March and harvested in early October. With cool temperatures, vast cropland area, and sufficient sunshine, the NE and NW are both important high-quality seed potato production regions in China. Potato in the NC and MLYR areas is grown from late February to mid-June, or from August to early November, avoiding the higher temperatures between mid-June and August. Potato in the SE is grown from mid- or late October to late December or early January, or from mid-January to early or mid-April. Rice–potato–rice, rice–-potato–potato–rice, and autumn potato–winter potato systems are common in the SE, where farmers realize high profits catering to potato demand during the winter. The SW plant either single or double potato crops per year, depending on elevation. Since the climate at altitudes over 2000 m is similar to that found in the NE and NW, a single cropping system is employed in these areas. The climate at elevations between 1000 and 2000 m is similar to that of the NC and MLYR, and conditions below 1000 m in the SW are similar to those found in the SE. There has been a steady increase in potato hectareage in the SE and SW following the rice crops in winter, and the continuous potato cropping system is still common in areas with two annual crops. Climate and soil nutrient characteristics for all six potato-producing areas are shown in Table 1.

Data Sources

To assess the relationship between nutrient uptake and tuber yield for potato in China, the datasets for QUEFTS model were collected from field experiments conducted by the International Plant Nutrition Institute (IPNI) China Program from 1992 to 2012 and 2017 that conducted by our group, and related published field experiments in peer reviewed journals of China Knowledge Resource Integrated database from 2000 to 2016 (www.cnki.net). Fertilization treatments included farmers' practice, optimal fertilization, and a series of nutrient omission plots of N, P, or K based on optimal fertilization treatment. In the optimal fertilization treatment, N, P, and K were applied in accordance with soil test and yield targets in the IPNI experiments. In published studies, the optimal fertilization treatment was selected by the highest yield and good field performance. In the farmers' practices treatment, fertilizer and field management were in accordance with farmers' traditional practice.

The QUEFTS Model

The QUEFTS model was used to simulate optimal nutrient uptake and used a large number of databases to evaluate relationship between tuber yield and nutrient uptake following a linear–parabolic–plateau model, the interactions of N, P, and K were considered to avoid deviation where a single or a few data to guide fertilizer application (Janssen et al., 1990, Smaling and Janssen, 1993; Witt et al., 1999). The maximum accumulation (*a*) and maximum dilution (*d*) boundary were calculated from the data set which removed outliers or potential errors, and used to estimate nutrient requirements by using QUEFTS model. The lower and upper 2.5 (Set I), 5.0 (Set II), and 7.5 (Set III) percentiles of the N, P, and K internal efficiency [IE, kg tuber per kg nutrient in the total plant nutrient (both tuber and

Table 1. Summary of experimental sites in different potato-producing regions of China.

Region†	Province	Climate	Main soil type	pH	Organic matter	Alkali-hydrolyzable N	Available P	NH_4OAc-K	Yield range	Case‡
					%	mg kg^{-1}			Mg ha^{-1}	
NE	Heilongjiang, Jilin, Liaoning	Cool temperate	Black soil, meadow soil	4.9–8.3	0.2–7.6	60.9–314.9	9.8–123.0	58.0–287.0	10.0–53.5	126
NW	Gansu, Inner Mongolia, Ningxia, Qinghai, Shaanxi, Xinjiang	Temperate	Loessial soil, fluvo-aquic soil, dark loessial soil, gray calcareous soil, chestnut soil, irrigation silting soil, cinnamon soil	6.0–8.9	0.2–5.1	19.2–211.0	4.3–168.0	14.0–338.2	1.1–74.5	641
NC	Hebei, Shandong, Shanxi, Henan	Temperate	Fluvo-aquic soil, meadow soil, cinnamon soil, loessial soil, chestnut soil	4.8–8.6	0.8–3.9	21.0–145.0	4.5–172.0	33.1–171.4	3.7–75.8	32
MLYR	Anhui, Zhejiang, Hubei, Hunan, Jiangxi, Jiangsu	Temperate sub-tropical	Yellow-brown soil, yellow soil	4.5–7.8	1.0–3.0	103.0–300.0	5.3–84.5	33.1–196.0	0.4–54.2	54
SE	Fujian, Guangdong, Guangxi	Tropical	Fluvo-aquic soil, paddy soil	4.7–7.1	0.3–3.9	40.0–166.3	6.2–188.0	18.0–248.4	3.9–59.5	26
SW	Yunnan, Guizhou, Sichuan, Chongqing, Tibet	Temperate sub-tropical	Red soil, yellow-brown soil, purple soil, paddy soil	4.5–8.2	0.4–6.1	47.5–330	3.8–112.1	25.0–950.0	1.3–75.9	107

† Region: NE, Northeast; NW, Northwest; NC, north-central; MLYR, Middle and lower reaches of the Yangtze River; SE, Southeast; SW, Southwest (equivalent to the acronyms found in the article text).

‡ The number of nutrient uptake data.

aboveground)] were used as *a* and *d* values. The nutrient requirements calculated by the QUEFTS model were similar for all three sets, except at the yield target approaching the potential yield. Since 2.5included a larger range of variability, it was then used to estimate balanced nutrient uptake and the relationship between tuber yield and nutrient accumulation, which were similar to previous reports (Witt et al., 1999; Liu et al., 2006; Xu et al., 2013). The balanced nutrient uptake from QUEFTS model was used to balance soil and plant based P and K nutrient maintenance in Nutrient Expert system.

The Nutrient Expert system is a nutrient decision support system based on SSNM and a modified QUEFTS model developed by the IPNI (Pampolino et al., 2012; Chuan et al., 2013a). In the Nutrient Expert, the fertilizer recommendation for N was determined by the yield response (yield gap between full NPK fertilizer application and N omission plot) and agronomic efficiency of N fertilizer application. The P and K rates were determined by yield response and plant-soil nutrient balance of P and K uptake for different target yield, and simulated nutrient uptake from the QUEFTS model was used to balance soil and plant maintenance of P and K for certain tuber yield targets.

On-farm field validation was conducted in the potato-producing provinces of Inner Mongolia (11), Jilin (5), Guizhou (8), and Sichuan (11) in 2017 based on Nutrient Expert method (Tables 2 and 3), to compare the difference between observed and simulated nutrient uptake. The fertilizer applications were 164 to 228 kg N ha^{-1}, 79 to 135 kg P_2O_5 ha^{-1}, and 109 to 240 kg K_2O ha^{-1}, and all experiments followed a standardized experimental protocol guided by local agricultural technicians. We collected both the senesced or the dead leaves and the alive leaves, and the tubers at harvest trying to collect all the leaves. The N, P, and K concentrations were measured for tuber and aboveground biomass at harvest.

Model Validation and Statistical Analyses

The root-mean-square error (RMSE), mean error (ME), normalized-RMSE (n-RMSE), and index of agreement (*d*) were used to evaluate deviations between QUEFTS model-simulated values and observed N, P, and K uptakes.

$$\mathrm{RMSE}=\sqrt{\frac{\sum_{i=1}^{n}\left(s_i-m_i\right)^2}{n}} \qquad [1]$$

$$\mathrm{ME}=\frac{\sum_{i=1}^{n}\left(s_i-m_i\right)}{n} \qquad [2]$$

Table 2. The characteristics of field experimental sites and soil properties (0–20 cm profile) in four provinces.

Region†	Province	Hectareage ratio‡	Main soil type	pH	Organic matter	Total N	Alkali-hydrolyzable N	Available P	NH_4OAc-K	Precipitation
		%			%	g kg^{-1}	mg kg^{-1}			mm
NE	Jilin	1.3	Black soil	5.8	2.6		107	44.6	182.2	398
NW	Inner Mongolia	9.7	Chestnut soil	7.5–8.0	1.1–3.7	1.37–1.5	64.2–172.4	3.0–47.4	59–160	304
SW	Guizhou	13.0	Yellow soil	4.7–7.8	2.1–3.7	0.47–1.0	116.2–145.3	6.6–46.7	187–408.6	1000
SW	Sichuan	14.3	Paddy soil	5.7–6.3	0.9–1.6	0.40–0.6	113.4	17.8–44.7	125.8–199.4	1200

† The region where the province belong.

‡ The provinces' acreage ratio of the total potato hectareage in the country.

Table 3. The experimental management details for the field study in four provinces.

Province	Farm location	No. of experiment	Varieties	Population	Plot size	Havest size	Sowing date	Harvest date
				plant ha^{-1}	m^2			
Jilin	Changling county	3	Favorita	60, 000	30	30	20 May	5 Oct.
	Changling county	2	Favorita					
Inner Mongolia	Wuchuan county	10	Kangnibeike, Kexin-1	40, 000	45	45	15 May	20 Sept.
	Jining district	1	Kangnibeike	50, 000				
Guizhou	Huaxi district	2	Weiyu-5	57, 142	30	30	8 Mar.	26 Sept.
	Qianxi county	1						
	Weining county	3						
	Weining county	2						
Sichuan	Wuling county	8	Favorita	85, 333	30	15	10 Sept.	12 Dec.
	Wuling county	3	Zhongshu-2					

$$\text{n-RMSE}=\frac{\text{RMSE}}{\bar{m}} \qquad [3]$$

$$d=1-\frac{\sum_{i=1}^{n}\left(s_i-m_i\right)^2}{\sum_{i=1}^{n}\left(\left|s_i-\bar{m}\right|+\left|m_i-\bar{m}\right|\right)^2} \qquad [4]$$

Here, m_i and s_i are the observed and simulated values, respectively; n is the number of observed values, and $\bar{m}$ is the total mean of the observed data across all experiments. The RMSE and ME were used to determine discrepancies for values having the same units of measure, while n-RMSE allowed comparison between values having different measurement units. The d value was used for comparisons between simulated and observed values in the range (0–1). If d value was less than 0.5, the model-simulated results were poor (Ren et al., 2015; He et al., 2018). The SPSS 19.0 software was utilized to analyze the significance differences between the means of simulated and observed values using the *t* test at the 5% significance level.

RESULTS

Characteristics of Yield and Nutrient Uptake

The overall average tuber yield (85% moisture content) for the field experiments in China was 25.1 Mg ha^{-1}, with a wide range of 0.4 to 75.9 Mg ha^{-1} (including the omission plots) (Table 4). The average HI was 0.74, with a range of 0.40 to 0.95, and 95% of the HI values were between 0.52 and 0.87 (Fig. 2).

The average N, P, and K concentrations in tubers were 16.8, 3.1, and 20.1 g kg^{-1}, with ranges of 3.5 to 38.8, 0.8 to 8.2, and 2.3 to 90.9 g kg^{-1}. The average nutrient concentrations found in the aboveground were 20.2 g N kg^{-1}, 3.1 g P kg^{-1}, and 21.8 g K kg^{-1}, with ranges of 0.2 to 45.2 g N kg^{-1}, 0.6–8.9 g P kg^{-1}, and 2.8 to 72.7 g K kg^{-1} (Table 4). The average N, P, and K accumulations in tubers were 2.2, 3.0, and 2.5 times those of aboveground biomass, respectively. In addition, the nutrient harvest

Table 4. Characteristics of yield and nutrient uptake of potato crops.

Parameter	Unit	Number†	Mean	SD	25%Q‡	Median	75%Q
Tuber yield	Mg ha^{-1}	6733	25.1	11.9	16.7	24.2	32.2
Harvest index	kg kg^{-1}	654	0.74	0.09	0.69	0.75	0.79
[N] in tuber	g kg^{-1}	568	16.8	6.0	12.2	16.3	20.1
[P] in tuber	g kg^{-1}	501	3.1	1.4	2.1	2.9	3.7
[K] in tuber	g kg^{-1}	521	20.1	12.3	13.9	17.1	23.5
[N] in aboveground	g kg^{-1}	424	20.2	8.0	14.5	19.4	23.6
[P] in aboveground	g kg^{-1}	378	3.1	1.7	1.5	2.8	4.2
[K] in aboveground	g kg^{-1}	395	21.8	16.3	9.7	17.5	29.1
Tuber N uptake	kg ha^{-1}	580	87.7	55.7	46.8	76.5	112.0
Tuber P uptake	kg ha^{-1}	511	15.8	10.3	7.6	14.5	21.1
Tuber K uptake	kg ha^{-1}	521	91.9	62.7	38.6	83.1	128.5
Aboveground N uptake	kg ha^{-1}	429	39.8	26.8	20.2	31.8	50.8
Aboveground P uptake	kg ha^{-1}	389	5.3	4.0	2.4	4.2	7.4
Aboveground K uptake	kg ha^{-1}	408	37.1	30.3	15.3	31.5	49.3
Plant N	kg ha^{-1}	606	129.9	69.7	82.0	118.2	162.8
Plant P	kg ha^{-1}	465	21.0	11.3	12.6	19.3	27.0
Plant K	kg ha^{-1}	497	131.8	81.2	69.5	122.4	180.4
NHI§	kg kg^{-1}	404	0.67	0.12	0.59	0.69	0.76
PHI	kg kg^{-1}	342	0.76	0.10	0.69	0.78	0.84
KHI	kg kg^{-1}	382	0.73	0.13	0.64	0.74	0.84

† Number of observations.

‡ 25%Q, Median, and 75%Q represent the 25th, 50th, and 75th percentiles of each dataset, respectively.

§ NHI, nutrient harvest index of N; PHI, nutrient harvest index of P; KHI, nutrient harvest index of K.

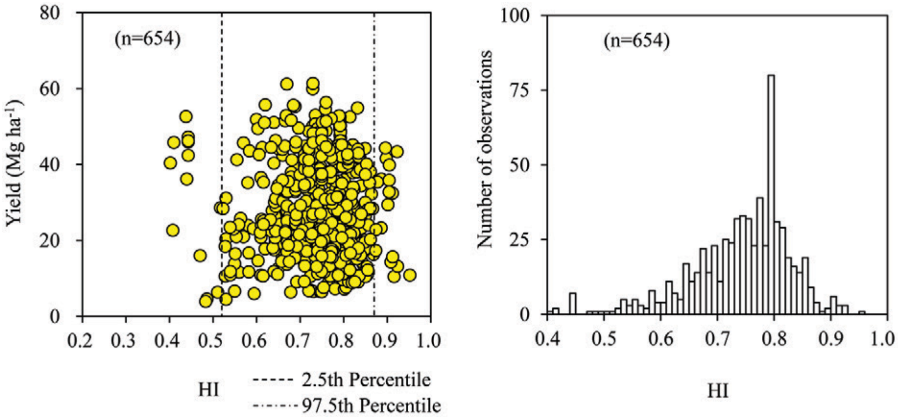

Fig. 2. Distribution of yield and harvest index of potato crops. † n is number of observations. ‡ HIs lower than 0.40 were excluded in the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model.

indices of N (NHI), P (PHI), and K (KHI) were 0.67, 0.76, and 0.73 kg kg^{-1}, respectively (Table 4). Potato tubers absorbed a substantial proportion of the nutrients.

Internal and Reciprocal Internal Efficiencies

The average IE of N, P, and K were 252.5, 1598.8, and 276.3 kg kg^{-1}, respectively. The average reciprocal internal efficiency (RIE, total plant nutrient requirement both tuber and aboveground to produce 1 Mg of tuber yield) of N, P, and K were 4.4, 0.7, and 4.4 kg Mg^{-1}, respectively (Table 5). Since the data for yields with at least one N, P, or K nutrient uptake were included, the IE (112.5–740.7 kg kg^{-1} N, 525.4–3822.8 kg kg^{-1} P, and 99.8–1111.8 kg kg^{-1} K) and the RIE (1.4–8.9 kg N Mg^{-1}, 0.3–1.9 kg P Mg^{-1}, and 0.9–5.4 kg K Mg^{-1}) both varied tremendously.

Estimating Optimum Nutrient Uptakes

The constants *a* and *d* were 133 and 463 kg kg^{-1} for N, 652 and 3030 kg kg^{-1} for P, and 119 and 790 kg kg^{-1} for K, respectively, and adopted to estimate the relationship between target yield and balanced plant N, P, and K requirements for different potential yields (30–60 Mg ha^{-1}) using QUEFTS model. The model estimated a linear relationship between target yield and optimum nutrient uptake until the target yield reached approximately 60 to 70% of the potential yield (Fig. 3).

Since the average potato yield in China was among 0.4 to 75.9 Mg ha^{-1} with averaged 25.1 Mg ha^{-1} across all sites, a potential yield of 60 Mg ha^{-1} was used to simulate the plant N, P, and K uptakes and the tuber yield rarely exceeded this level in China (Table 6). The QUEFTS model simulated plant nutrient requirements of 4.0 kg N, 0.7 kg P, and 3.5 kg K in the linear section of the uptake curve to produce 1 Mg of tubers, with corresponding tuber nutrient demands of 2.9 kg N, 0.5 kg P, and 2.3 kg K to produce 1 Mg of tubers. The optimal N/P/K ratios were 1.0:0.2:0.9 for total potato plants and 1.0:0.2:0.8 for tubers. Since 71.8% N, 69.9% P, and 66.1% K were in the tubers themselves and thus were removed from the fields, balanced fertilization may avoid the luxury uptake of K in tubers.

Field Validation

The relationship between QUEFTS model-simulated and Nutrient Expert treatment-observed nutrient uptakes was analyzed (Fig. 4). The RMSE, n-RMSE, ME, and *d* values were 35.6kg ha^{-1}, 24.4%, −8.2 kg ha^{-1}, and 0.88 for N; 9.7 kg ha^{-1}, 37.7%, −1.4 kg ha^{-1}, and 0.70 for P; and 116.4 kg ha^{-1}, 62.8%, −66.9 kg ha^{-1}, and 0.53 for K, respectively. The points around the 1:1 line showed some deviation and luxury uptake for observed K in Guizhou and Sichuan. The observed K uptake ($P < 0.05$) was significantly higher than simulated in Sichuan and Guizhou, respectively. The observed N and K uptake in Nutrient Expert treatment ($P < 0.05$) were significantly lower than simulated in Jilin, respectively.

DISCUSSION

The average tuber yield in the present study was higher than the national average of 15.4 Mg ha^{-1} and the global average of 17.9 Mg ha^{-1} from 2000 to 2016 (FAO, 2016). Potato production co-exists with poverty and is more adaptable to resource-poor areas in China than other food crops. Regions benefiting from improved potato varieties, better field management techniques, and more favorable soil nutrient and climate conditions experienced great improvements in potato yield (Bélanger et al., 2001; Moinuddin et al., 2006; Devaux et al., 2014; Tein et al., 2014).

The HI was slightly affected by N, P, and K supply levels and more stable than total biomass from the study of Sandaña and Kalazich (2015). The HIs lower than 0.40 were excluded as crops suffered from either disease or some sort of water, abiotic, or biotic stress in this case (Hay, 1995; Witt et al., 1999). And potato normally has a higher HI than other crops (0.4–0.5), such as wheat, corn (*Zea mays* L.), and rice (Hay, 1995; Sandaña and Kalazich, 2015).

White et al. (2009) estimated the average nutrient concentrations in tubers to be 15.6 g N kg^{-1}, 2.4 g P kg^{-1}, and 20.0 g K kg^{-1} between and within potato species, with ranges of

Table 5. Characteristics of the internal efficiency (IE, kg tuber per kg nutrient in the total plant) and its reciprocal internal efficiency (RIE, total plant nutrient requirement both tuber and aboveground to produce 1 Mg of tuber yield) for potato plants in China.

Parameter	Unit	n†	Mean	SD	25%Q‡	Median	75%Q
IE-N	kg kg^{-1}	507	252.5	89.0	186.9	239.6	297.6
IE-P	kg kg^{-1}	373	1598.8	652.3	1063.3	1470.1	1997.8
IE-K	kg kg^{-1}	439	276.3	150.6	183.9	240.0	330.5
RIE-N	kg Mg^{-1}	507	4.4	1.4	3.4	4.2	5.4
RIE-P	kg Mg^{-1}	373	0.7	0.3	0.5	0.7	0.9
RIE-K	Kg Mg^{-1}	439	4.4	1.7	3.0	4.2	5.4

† Number of observations.

‡ 25%Q, Median, and 75%Q represent the 25th, 50th, and 75th percentiles of each dataset, respectively.

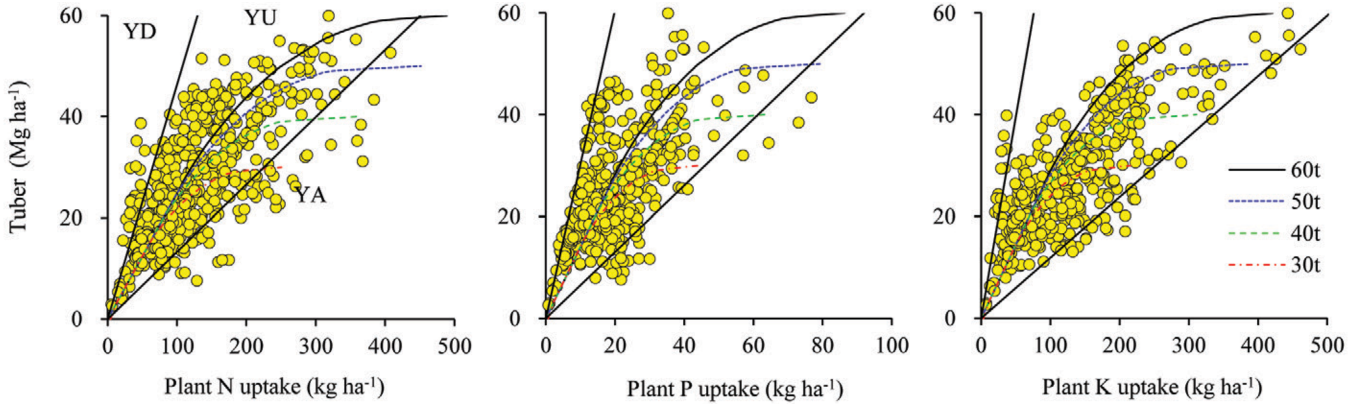

Fig. 3. Relationship between potato yield and N, P, and K accumulations for different potential yields simulated by the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model for potato crops in China. The boundary lines correspond to the lines of maximum accumulation (YA) and maximum dilution (YD), YU represent balance nutrient uptake as predicted by QUEFTS model. The yield potential ranged from 30 to 60 Mg ha^{-1}.

11.2 to 19.9 g N kg^{-1}, 1.3 to 3.0 g P kg^{-1}, and 13.8 to 21.3g K kg^{-1}. These average values were higher than those found in the present study. Earlier studies, though not statistically robust, confirmed that higher-yielding varieties were observed in lower nutrient concentrations than lower-yielding varieties (Tekalign and Hammes, 2005; White et al., 2009).

Duan et al. (2014) estimated an average required nutrient uptake of 5.3 kg N, 0.6 kg P, and 5.0 kg K to produce 1 Mg of tubers. Their experiments were long-term and multi-site and featured optimal management, which located in Wuchuan county and Chayouzhongqi in Inner Mongolia of China. Their uptake values ranged from 4.0 to 7.6 kg N Mg^{-1}, 0.4 to 1.1 kg P Mg^{-1}, and 3.0 to 7.8 kg K Mg^{-1} and the average yield was 37.4 Mg ha^{-1} (24.4–60.2 Mg ha^{-1}). The higher RIEs of N and K in Duan et al. (2014) study were likely related to the higher yield levels (Yang et al., 2017). However, overfertilization and high soil nutrient availability led to an increasing rate of higher RIEs with lower yields, confirming the presence of luxury consumption throughout the potato growth cycle (Kang et al., 2014). Furthermore, given the large supply of indigenous soil nutrients, the fertilization recommendation based on RIE was not reliable (Rosen et al., 2014; Ruark et al., 2014). Soil nutrient conditions, plant nutrient demands, and the interactions between N, P, and K must be taken into consideration when proposing a fertilizer recommendation. The optimal N/P/K ratios were 1.0:0.2:0.9 for potato plants in the present study, while Kumar et al. (2018) estimated the optimal N:P:K ratio was 1.0:0.2:1.3 with higher potassium demand using QUEFTS model.

Field validation results showed that widespread unreasonable fertilization existed in the farmers' practice treatment, and also that Nutrient Expert combined with QUEFTS model provided a feasible fertilization recommendation that reduced the risk of environment pollution and increase yield (Pampolino et al., 2012). Since the points around the 1:1 line showed some

Table 6. Balanced nutrient requirement of the reciprocal internal efficiencies of N, P, and K as simulated by the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model for particular target yields of potato crops in China (60 Mg ha^{-1} potential yield).

	Plant RIE†			Tuber RIE‡			Ratio in tuber§		
Yield	N	P	K	N	P	K	N	P	K
Mg ha^{-1}	kg nutrient Mg^{-1} yield						%		
0	0	0	0	0	0	0	0	0	0
6	4.0	0.7	3.5	2.9	0.5	2.3	71.8	69.9	66.1
12	4.0	0.7	3.5	2.9	0.5	2.3	71.8	69.9	66.1
18	4.0	0.7	3.5	2.9	0.5	2.3	71.8	69.9	66.1
24	4.0	0.7	3.5	2.9	0.5	2.3	71.8	69.9	66.1
30	4.0	0.7	3.5	2.9	0.5	2.3	72.4	70.4	66.6
35	4.2	0.7	3.6	3.0	0.5	2.4	72.2	70.3	66.5
40	4.4	0.8	3.8	3.2	0.5	2.5	72.2	70.3	66.5
45	4.6	0.8	4.0	3.3	0.6	2.7	72.2	70.3	66.4
48	4.8	0.9	4.2	3.5	0.6	2.8	72.2	70.3	66.4
50	5.0	0.9	4.3	3.6	0.6	2.9	72.2	70.3	66.4
55	5.6	1.0	4.8	4.0	0.7	3.2	72.2	70.2	66.4
56	5.8	1.0	5.0	4.2	0.7	3.3	72.2	70.2	66.4
57	6.0	1.1	5.2	4.3	0.7	3.4	72.2	70.2	66.4
58	6.3	1.1	5.4	4.5	0.8	3.6	72.2	70.3	66.4
59	6.7	1.2	5.8	4.8	0.8	3.8	72.2	70.3	66.5
60	8.1	1.4	7.0	6.7	1.1	5.3	82.0	79.8	75.5

† Expressed as kilogram of total plant nutrient requirement (both tuber and aboveground matter) to produce per megagram of tuber yield.

‡ Expressed as kilogram of tuber nutrient requirement to produce per megagram of tuber yield.

§ Expressed as the ratio of nutrient in tuber of total plant.

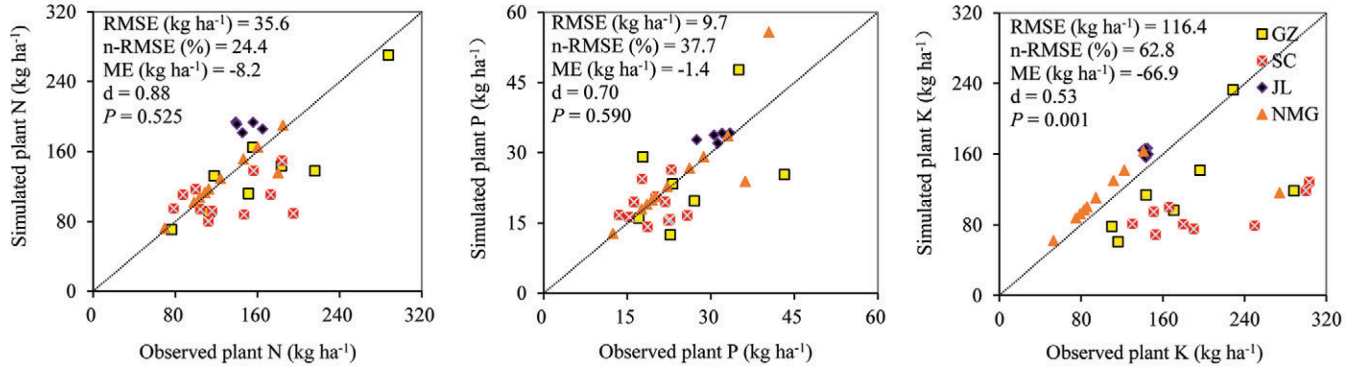

Fig. 4. Relationship between Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model-simulated and observed N, P, and K uptakes for potatoes in different regions of China. † GZ, Guizhou; SC, Sichuan; JL, Jilin; NMG, Inner Mongolia. ‡ The *t* test at the 5% level was used to analyze the means of the simulated and observed values; if $P > 0.05$, there was no significant difference between the simulated and observed nutrient uptakes.

deviation and luxury uptake for observed K in Guizhou and Sichuan (Fig. 4), which had greater initial K availability in the soil (Table 2). The high soil NH_4OAc-K content and high K_2O application were the major reason to a luxury K uptake in Guizhou (Kang et al., 2014), we should do field experiments and correct K recommendation further. However, in Inner Mongolia, only one point was far from the 1:1 line, indicating that there was no clear luxury K uptake in this site, mainly because the initial K availability in the soil was much lower than in Guizhou and Sichuan sites.

CONCLUSIONS

There was a wide variation in tuber yield and nutrient uptake corresponding to the broad range of climatic conditions, soil types, and cropping systems found in China. The average tuber yield of potato crops in China was 25.1 Mg ha^{-1}. The average N, P, and K accumulations were 87.7, 15.8, and 91.9 kg ha^{-1} in tubers, and 39.8, 5.3, and 37.1 kg ha^{-1} in the aboveground, respectively. The QUEFTS model predicted that target yield and nutrient uptake would be linearly distributed until the target yield reached approximately 60 to 70% of the potential yield. The QUEFTS model simulated that 4.0 kg N, 0.7 kg P, and 3.5 kg K were required for total plant to produce 1 Mg of tuber in the linearly distributed portion of the uptake curve, as well as corresponding requirements of 2.9 kg N, 0.5 kg P, and 2.3 kg K for tuber to produce 1 Mg of tuber. Tuber N, P, and K accounted for 71.8, 69.9, and 66.1% of the nutrients in the potato plant in the linearly distributed portion, respectively. Field validation demonstrated that the QUEFTS model could be used to simulate potato nutrient uptake and provide appropriate parameters for Nutrient Expert system, and thus help to optimize fertilization recommendations in China.

ACKNOWLEDGMENTS

This research was supported by the National Key Research and Development Program of China (no. 2016YFD0200101), the CAAS-IPNI Joint Lab for Plant Nutrition Innovation Research (no. 161032019047). Authors are thankful to the farmers and scientists for their patience during the field experiments in this study.

REFERENCES

Alva, A., M.S. Fan, C. Qing, C. Rosen, and H. Ren. 2011. Improving nutrient-use efficiency in Chinese potato production: Experiences from the United States. J. Crop Improv. 25:46–85. doi:10.1080/15427528.2011.538465

Bai, Y.L. 2015. Review on research in plant nutrition and fertilizers. (In Chinese, with English abstract.) Zhongguo Nong Ye Ke Xue 48:3477–3492. doi:10.3864/j.issn.0578-1752.2011.20.009

Bélanger, G., J.R. Walsh, J.E. Richards, P.H. Milburn, and N. Ziadi. 2001. Critical nitrogen curve and nitrogen nutrition index for potato in Eastern Canada. Am. J. Potato Res. 78:355–364. doi:10.1007/BF02884344

Byju, G., M. Nedunchezhiyan, A.C. Hridya, and S. Soman. 2016. Site-specific nutrient management for cassava in southern India. Agron. J. 108:830–840. doi:10.2134/agronj2015.0263

Chen, Y., M.S. Fan, W.Q. Kang, and Y.L. Qin. 2012. Evaluation and present situation of fertilization for potato in hilly country of Yinshan in Inner Mongolia. (In Chinese, with English abstract.) Soils Fert. China 2:104–108.

Chuan, L.M., P. He, J.Y. Jin, S.T. Li, C. Grant, X.P. Xu, S.J. Qiu, S.C. Zhao, and W. Zhou. 2013b. Estimating nutrient uptake requirements for wheat in China. Field Crops Res. 146:96–104. doi:10.1016/j.fcr.2013.02.015

Chuan, L.M., P. He, M.F. Pampolino, A.M. Johnston, J.Y. Jin, X.P. Xu et al. 2013a. Establishing a scientific basis for fertilizer recommendations for wheat in China: Yield response and agronomic efficiency. Field Crops Res. 140:1–8. doi:10.1016/j.fcr.2012.09.020

Cui, Z.L., H.Y. Zhang, X.P. Chen, C.C. Zhang, W.Q. Ma, C.D. Huang et al. 2018. Pursuing sustainable productivity with millions of smallholder farmers. Nature (London) 555:363–366. doi:10.1038/nature25785

Devaux, A., P. Kromann, and O. Ortiz. 2014. Potatoes for sustainable global food security. Potato Res. 57:185–199. doi:10.1007/s11540-014-9265-1

Dobermann, A., C. Witt, D. Dawe, S. Abdulrachman, H.C. Gines, R. Nagarajan et al. 2002. Site-specific nutrient management for intensive rice cropping systems in Asia. Field Crops Res. 74:37–66. doi:10.1016/S0378-4290(01)00197-6

Duan, Y., J. Zhang, H.C. Li, P.Y. Zhao, D.B Tuo, J.Q. Yao, H. An, and Y.Y. Jia. 2014. Fertilization effect and nutrition use efficiency of potato in Inner Mongolia. (In Chinese, with English abstract.). Soils 46:212–217.

FAO. 2016. FAOSTAT Database-Agricultural production. Food and Agriculture Organization of the United Nations. http://www.fao.org/faostat/en/#data/QC (accessed 20 May 2018)

Hay, R. 1995. Harvest index: A review of its use in plant breeding and crop physiology. Ann. Appl. Biol. 126:197–216. doi:10.1111/j.1744-7348.1995.tb05015.x

He, W.T., J.Y. Yang, C.F. Drury, W.N. Smith, B.B. Grant, P. He et al. 2018. Estimating the impacts of climate change on crop yields and N_2O emissions for conventional and no-tillage in Southwestern Ontario, Canada. Agric. Syst. 159:187–198. doi:10.1016/j.agsy.2017.01.025

Janssen, B.H., F.C.T. Guiking, D. van der Eijk, E.M.A. Smaling, J. Wolf, and H. van Reuler. 1990. A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). Geoderma 46:299–318. doi:10.1016/0016-7061(90)90021-Z

Kang, W.Q., M.S. Fan, Z. Ma, X.H. Shi, and H.L. Zheng. 2014. Luxury absorption of potassium by potato plants. Am. J. Potato Res. 91:573–578. doi:10.1007/s12230-014-9386-8

Kumar, P., G. Byju, B.P. Singh, J.S. Minhas, and V.K. Dua. 2016. Application of QUEFTS model for site-specific nutrient management of NPK in sweet potato (*Ipomoea batatas L*. Lam). Commun. Soil Sci. Plant Anal. 47:1599–1611. doi:10.1080/00103624.2016.1194989

Kumar, P., V.K. Dua, J. Sharma, G. Byju, J.S. Minhas, and S.K. Chakrabarti. 2018. Site-specific nutrient requirements of NPK for potato (*Solanum tuberosum* L.) in Western Indo-gangetic plains of India based on QUEFTS. J. Plant Nutr. 41:1988–2000. doi:10.1080/01904167.2018.1484135

Li, S.T., Y. Duan, T.W. Guo, P.L. Zhang, P. He, A. Johnston, et al. 2015. Potassium management in potato production in Northwest region of China. Field Crops Res. 174:48–54. doi:10.1016/j.fcr.2015.01.010

Li, S.T., and J.Y. Jin. 2011. Characteristics of nutrient input/output and nutrient balance in different regions of China. (In Chinese, with English abstract.) Zhongguo Nong Ye Ke Xue 44:4207–4229.

Liu, R.M., M.P. Fan, Y.Z. Fu, J. Zhou, Y. Zheng, and L. Tang. 2014. Relationship between fertilization rate and fertilizer partial factor productivity in potato production in Yunnan province. (In Chinese, with English abstract.) Turang Xuebao 51:753–760.

Liu, M.Q., Z.R. Yu, Y.H. Liu, and N.T. Konijn. 2006. Fertilizer requirements for wheat and maize in China: The QUEFTS approach. Nutr. Cycling Agroecosyst. 74:245–258. doi:10.1007/s10705-006-9002-5

Moinuddin, K.S., S.K. Bansal, and N.S. Pasricha. 2006. Influence of graded levels of potassium fertilizer on growth, yield, and economic parameters of potato. J. Plant Nutr. 27:239–259. doi:10.1081/PLN-120027652

Pampolino, M.F., C. Witt, J.M. Pasuquin, A. Johnston, and M.J. Fisher. 2012. Development approach and evaluation of the Nutrient Expert software for nutrient management in cereal crops. Comput. Electron. Agric. 88:103–110. doi:10.1016/j.compag.2012.07.007

Pasuquin, J.M., M.F. Pampolino, C. Witt, A. Dobermann, T. Oberthür, M.J. Fisher, and K. Inubushi. 2014. Closing yield gaps in maize production in Southeast Asia through site-specific nutrient management. Field Crops Res. 156:219–230. doi:10.1016/j.fcr.2013.11.016

Ren, T., J. Zou, Y. Wang, X.K. Li, R.H. Cong, and J.W. Lu. 2015. Estimating nutrient requirements for winter oilseed rape based on QUEFTS analysis. J. Agric. Sci. 154:425–437. doi:10.1017/S0021859615000301

Rosen, C.J., K.A. Kelling, J.C. Stark, and G.A. Porter. 2014. Optimizing phosphorus fertilizer management in potato production. Am. J. Potato Res. 91:145–160. doi:10.1007/s12230-014-9371-2

Ruark, M.D., K.A. Kelling, and L.W. Good. 2014. Environmental concerns of phosphorus management in potato production. Am. J. Potato Res. 91:132–144. doi:10.1007/s12230-014-9372-1

Sandaña, P., and J. Kalazich. 2015. Ecophysiological determinants of tuber yield as affected by potato genotype and phosphorus availability. Field Crops Res. 180:21–28. doi:10.1016/j.fcr.2015.05.005

Sattari, S.Z., M.K. van Ittersum, A.F. Bouwman, A.L. Smit, and B.H. Janssen. 2014. Crop yield response to soil fertility and N, P, K inputs in different environments: Testing and improving the QUEFTS model. Field Crops Res. 157:35–46. doi:10.1016/j.fcr.2013.12.005

Setiyono, T.D., D.T. Walters, K.G. Cassman, C. Witt, and A. Dobermann. 2010. Estimating maize nutrient uptake requirements. Field Crops Res. 118:158–168. doi:10.1016/j.fcr.2010.05.006

Smaling, E.M.A., and B.H. Janssen. 1993. Calibration of QUEFTS, a model predicting nutrient uptake and yields from chemical soil fertility indices. Geoderma 59:21–44. doi:10.1016/0016-7061(93)90060-X

Tein, B., K. Kauer, V. Eremeev, A. Luik, A. Selge, and E. Loit. 2014. Farming systems affect potato (*Solanum tuberosum* L.) tuber and soil quality. Field Crops Res. 156:1–11. doi:10.1016/j.fcr.2013.10.012

Tekalign, T., and P.S. Hammes. 2005. Growth and productivity of potato as influenced by cultivar and reproductive growth. Sci. Hortic. (Amsterdam) 105:29–44. doi:10.1016/j.scienta.2005.01.021

Teng, Z.F., C. Zhang, and Y.Z. Wang. 1989. Study on China's potato-cultivation divisions. (In Chinese, with English abstract.). Zhongguo Nong Ye Ke Xue 22:35–44.

White, P.J., J.E. Bradshaw, M. Finlay, G. Ramsay, J.P. Hammond, and M.R. Broadley. 2009. Relationships between yield and mineral concentrations in potato tuber. HortScience 44:6–11. doi:10.21273/HORTSCI.44.1.6

Witt, C., A. Dobermann, S. Abdulrachman, H.C. Gines, G.H. Wang, R. Nagarajan et al. 1999. Internal nutrient efficiencies of irrigated lowland rice in tropical and subtropical Asia. Field Crops Res. 63:113–138. doi:10.1016/S0378-4290(99)00031-3

Xu, X.P., P. He, M.F. Pampolino, L.M. Chuan, A.M. Johnston, S.J. Qiu et al. 2013. Nutrient requirements for maize in China based on QUEFTS analysis. Field Crops Res. 150:115–125. doi:10.1016/j.fcr.2013.06.006

Xu, X.P., J.G. Xie, Y.P. Hou, P. He, M.F. Pampolino, S.C. Zhao, S.J. Qiu, A.M. Johnston, and W. Zhou. 2015. Estimating nutrient uptake requirements for rice in China. Field Crops Res. 180:37–45. doi:10.1016/j.fcr.2015.05.008

Yang, F.Q., X.P. Xu, W. Wang, J.C. Ma, D. Wei, P. He et al. 2017. Estimating nutrient uptake requirements for soybean using QUEFTS model in China. PLoS One 12:e0177509. doi:10.1371/journal.pone.0177509