doi: 10.17221/417/2017-PSE

Using QUEFTS model for estimating nutrient requirements of maize in the Northeast China

Wenting JIANG, Xiaohu LIU*, Wen QI, Xiaonan XU, Yucui ZHU

College of Land and Environment, Shenyang Agriculture University, Shenyang, Liaoning, P.R. China

**Corresponding author: liuxiaohumail@163.com*

ABSTRACT

Jiang W.T., Liu X.H., Qi W., Xu X.N., Zhu Y.C. (2017): Using QUEFTS model for estimating nutrient requirements of maize in the Northeast China. Plant Soil Environ., 63: 498–504.

Accurate estimating of the balanced nutrition for maize is necessary for optimizing fertilizer management to prevent nutrient supply surplus or deficiency. Data from 300 field experiments in the Northeast China conducted between 2006 and 2011 were gathered to study the characteristics of maize yield, and using the QUEFTS model to estimate the balanced nutrition at different yield potential. The average grain yield was 10 427 kg/ha, and average internal efficiencies were 54.3, 251.5 and 78.2 kg grain per kg plant nitrogen (N), phosphorus (P) and potassium (K), respectively. With the harvest index values < 0.40 as outliers were excluded, the model simulated a linear-parabolic-plateau curve for the balanced N, P and K uptake when the initial yield target increased to the yield potential levels of 10 000 to 14 000 kg/ha. When the yield target reached approximately 60–70% of the yield potential, 16.7 kg N, 3.8 kg P, and 11.4 kg K were required to produce 1000 kg grain. The corresponding internal efficiencies were 60.0, 265.7 and 88.0 kg grain per kg plant N, P and K, respectively. These results contributed to improving nutrient use efficiency, and to demonstrate that the QUEFTS model could be a promising approach for estimating the balanced nutrition.

Keywords: *Zea mays* L.; nutrient uptake; internal efficiency; fertilization; production

Global population size is predicted to increase from 7.2 billion to over 9 billion by 2050 (according to the United Nations world population prediction), which poses an unprecedented challenge for global crop production systems. Besides, global demands for major grains, such as maize (*Zea mays* L.), are projected to increase by 70%, forced by the human population requirements for food, fiber and fuel (Fedoroff et al. 2010, Tilman et al. 2011). Fertilizer use is an efficient way to increase yields and maintain food security (Dobermann et al. 1998, Wu et al. 2013), but an increasing number of research demonstrated that excessive or imbalanced mineral-fertilizer application by farmers has become a common practice in China, resulting in long-term production stagnation and severe soil degradation (Zhao et al. 2006, Cui et al. 2010). According to the production reports, maize yield in China has increased from 1.14 t/ha to 5.2 t/ha between 1961 and 2009. However, yield has stagnated and declined gradually in a recent decade, which is concurrent with a linear increase in nutrient inputs (Ma et al. 2015). Additionally, approximately 24–39% of global main maize production areas also appear to be declining (Ray et al. 2012, Grassini et al. 2013). Obviously, there is imbalance between fertilizer application and nutrient requirements for crop, resulting in both reduced crop yields and inefficient fertilizer use.

Supported by the Research and Demonstration of High Efficiency Fertilization Technology of Maize in Northeast Plain, Project No. 2015BAD23B05-02.

doi: 10.17221/417/2017-PSE

To address this problem, fertilizer recommendations have mainly focused on measuring soil properties and regulating nitrogen (N) nutrient supply based on the residual nitrate-N concentration in soil (Dai et al. 2015, Wang et al. 2016). These fertilizer recommendation methods are effective, but the costs to complex field sampling are high and field trails needs to be set annually owing to different soil types in China (Huang et al. 2006). Besides, the nutrient recommendation algorithms could be used for quantifying crop nutrient requirements to optimize nutrient management. However, most previous studies only considered a single nutrient, thereby neglecting the interactions between more plant nutrients (Yang et al. 2017).

The QUEFTS model could help resolve these issues, concerning the interactions between nutrients, which is the most important and distinguishing character compared with other models. Thus, the model was used as an efficient tool for quantifying balanced nutrient requirements for a yield target to provide a support for fertilizer recommendations. Currently, the QUEFTS model has been successfully applied to different crops, including maize, rice and wheat in countries such as Africa, USA, India and China (Saı'Dou et al. 2003, Liu et al. 2006, Das et al. 2009, Buresh et al. 2010).

Differently from the previous studies, this paper emphasizes that the necessity to calculate the balanced nutrition for maize by using QUEFTS model at a regional scale (Northeast China) has not yet been attempted. Li et al. (2011) reported that to figure out the nutrient balance, input or output in different parts of China is meaningful for fertilizer recommendations. Thus, the objectives of the study were to: (1) analyse the characteristics of grain yield and internal efficiency; (2) estimate the balanced N, phosphorus (P) and potassium (K) requirements for maize at different yield potential.

MATERIAL AND METHODS

Data sources. The database used for this study was obtained from 300 field experiments at 52 maize experimental sites located in the Liaoning Province (38°43'N–43°26'N, 118°53'E–125°46'E), Northeast China from 2006 to 2011 (Figure 1).

The region has a continental monsoon climate with the average annual temperature of 7.0–8.3°C, and 136–180 frost-free days. The mean annual precipitation ranged between 433.5–1077.8 mm, primarily from June to September. The soil is classified as Haplic-Udic Luvisols, and the chemical properties are as follows: pH ranged from 5.56 to 7.91, alkaline hydrolyse N, available P and avail-

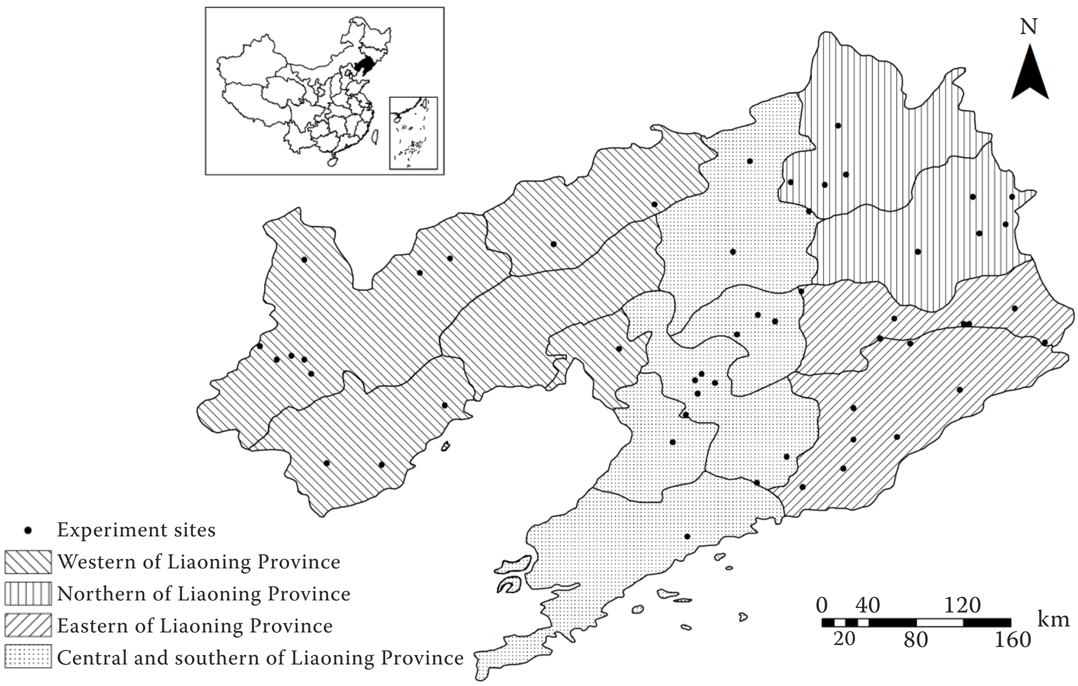

Figure 1. Geographical distribution of the experimental sites of maize in the Liaoning province of China

doi: 10.17221/417/2017-PSE

able K were in the range of 65.54–120.68 mg/kg, 12.6–48.58 mg/kg, 86.58–142.83 g/kg, respectively. Soil organic carbon ranged from 4.8 to 11.3 g/kg, total N ranged from 0.56 to 1.33 g/kg.

Experimental design. At each experimental site, the plots size ranged from 30 to 60 m^2 and were arranged in a randomized block design with three replications per treatment. The treatments were: (1) no fertilizer (CK); (2) optimal recommended fertilization (OPT), according to the soil tests and local maize cultivation technology with the level of N: 180–240 kg N/ha, P: 39.6–66.0 kg P/ha, and K: 99.6–124.5 kg K/ha; (3) no N fertilizer (N_0): only P (39.6–66.0 kg P/ha) and K (99.6–124.5 kg K/ha) fertilizers were used in the plots; (4) no P fertilizer (P_0): only N (180–240 kg N/ha) and K (99.6–124.5 kg K/ha) fertilizers were used in the plots; (5) no K fertilizer (K_0): only N (180–240 kg N/ha) and P (39.6–66.0 kg P/ha) fertilizers were used in the plots.

The N, P and K fertilizers were applied as urea (46% N), superphosphate (16% P), and potassium chloride (52% K), respectively. Pesticides and herbicides were applied to fields during the maize growing season following conventional practices to control pests and weeds.

Plant sampling and analysis. At maturity, plants were harvested manually by hand (cut 10 cm above the ground) in each plot; stubble left in the field was negligible. The fresh grain and straw samples were dried at 80°C and weighed. Subsamples were passed through a 1 mm sieve, and digested with H_2SO_4-H_2O_2, after which the N, P and K concentrations were measured by using the micro-Kjeldahl procedure, vanadate molybdate-yellow colorimeter and flame spectrophotometer, respectively (Bao 2000).

Calculation. Harvest index (HI), nutrient harvest index ($HI_{N/P/K}$), internal efficiency (IE), and reciprocal internal efficiency (RIE) were calculated with the formulas:

$$HI = \frac{Y}{DM}$$

$$HI_{N/P/K} = \frac{Y_{N/P/K}}{U_{N/P/K}}$$

$$IE_{N/P/K} = \frac{Y}{U_{N/P/K}}$$

$$RIE_{N/P/K} = \frac{U_{N/P/K}}{Y} \times 1000$$

Where: Y – grain yield; DM – total above-ground dry matter; $Y_{N/P/K}$ – N, P or K accumulated in grain; $U_{N/P/K}$ – N, P or K accumulated in the above-ground plant dry matter.

Model introduction. Data were collected from all experimental sites. First, the analysis of the data was performed, including grain yield, plant accumulation of N, P and K, and internal efficiency. In our study, the approach to calculation of the balanced nutrient uptake at different yield potential majorly adhered to Witt et al. (1999). Thus, a description of steps is as follows:

1. Sifting through the data and removing outliers. A prerequisite for applying the QUEFTS model was that the database was not to be limited by biotic or abiotic stress other than N, P or K supply (Setiyono et al. 2010). Thus, the data where the HI was less than 0.4 were supposed to have suffered from drought or diseases during grain filling and those should be excluded before using the QUEFTS.
2. For each nutrient, the borderlines to the relationship of grain yield and nutrient uptake were determined. The slope of two borderlines represents the maximum accumulation (*a*) and maximum dilution (*d*) of a particular nutrient, respectively. (Witt et al. 1999, Xu et al. 2013). The values of *a* and *d* were mostly calculated as the 2.5th and 97.5th percentiles of the calculated IE of a particular nutrient.

With the *a* and *d* coefficients determined and the yield potential set, a spreadsheet version of the QUEFTS model was used to calculate the balanced N, P and K requirements of maize at different yield potential levels. The QUEFTS model was run, each time making a slight increase as the initial yield target of 1000 kg/ha gradually approached to the yield potential. N is shown as an example (Figure 2).

RESULTS AND DISCUSSION

General overview of database. The grain yield ranged from 2543 to 14 196 kg/ha (Table 1) and the yield levels were mostly distributed in the range of 8000–9000 kg/ha (17.3%) and 9000–11 000 kg/ha (19.3%), with low frequency distribution in the extremely high or low yield ranges (Figure 3). The average grain yield in this study was 8858 kg/ha (Table 1), which was approximately 38.2% and 42.9% higher than those from 2006 to 2011 in the global scale (5468 kg/ha) and in China (5075 kg/ha), respectively (FAO 2011). Grain yield observed in our study was attributable to the utilization of new

doi: 10.17221/417/2017-PSE

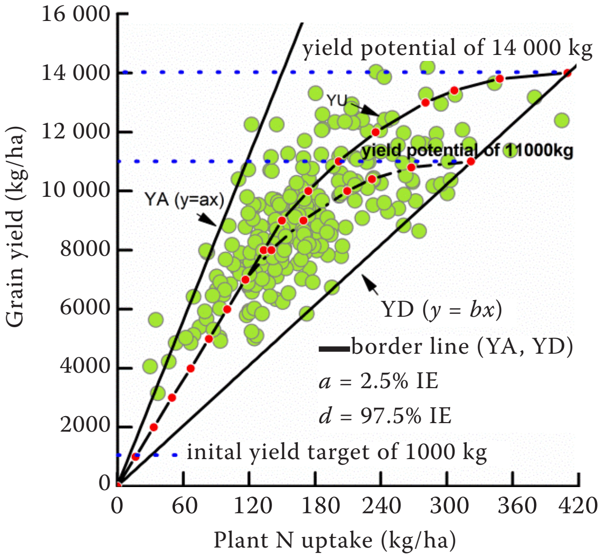

Figure 2. The relationship between grain yield and plant nitrogen (N) uptake. YU – balanced N requirement to achieve a yield potential; YA, YD – borderline of maximum accumulation and dilution of N in the above-ground dry matter. Envelope coefficients of *a* and *d* represent the slopes of YA and YD; IE – internal efficiency

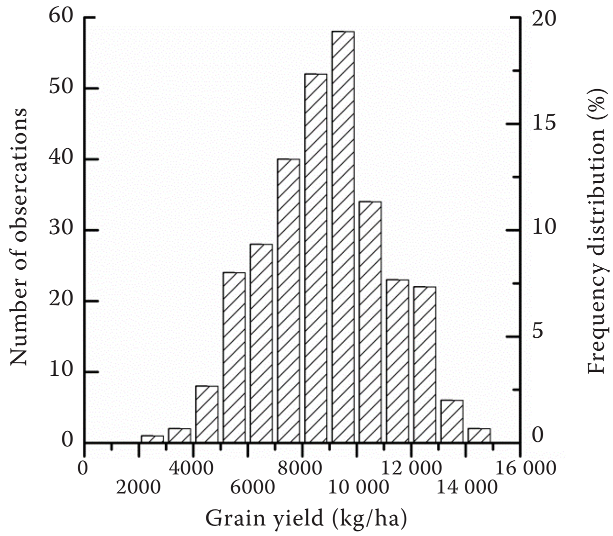

Figure 3. The distribution of different ranges of grain yield conducted across 52 experimental sites (n = 300)

cultivars and good field-management practices, which indicated that both breeding and cultivation had been gradually matured as well.

The nutrient concentrations within each plant component also had a broad variation (Table 1). On average, the total above-ground N, P and K accumulation were 176.1 kg/ha, 36.9 kg/ha, and 134.8 kg/ha, respectively, indicating an N:P:K ratio of 4.77:1:3.65 in the plant (Table 1). The average N, P and K harvest indexes were 0.61, 0.81, and 0.23, respectively (Table 1). In other words, about 61% of the N, 81% of the P, and 23% of the K in the

Table 1. Statistics of all maize characteristics data (n = 300) from field experiments in the Northeast China from 2006 to 2011

Parameter		Unit	Mean	Minimum	25% quartile	Median	75% quartile	Maximum
Grain yield		(kg/ha)	8858	2543	7382	8851	10 334	14 196
Harvest index		(g/g)	0.46	0.20	0.43	0.46	0.50	0.69
Grain	N	(g/kg)	11.68	2.61	10.16	11.76	13.47	19.37
	P		3.41	0.96	2.85	3.35	3.90	6.86
	K		3.05	0.10	2.50	2.91	3.49	6.75
Straw	N		6.75	1.86	4.76	6.46	8.1	17.35
	P		0.67	0.21	0.50	0.63	0.79	1.68
	K		10.21	1.34	6.87	9.94	13.31	23.13
Plant	N	(kg/ha)	176.1	29.9	129.1	168.2	214.5	453.9
	P		36.9	11.2	28.5	35.2	45.5	77.9
	K		134.8	25.9	90.3	124.9	171.0	407.7
Harvest index	N	(kg/kg)	0.61	0.18	0.53	0.62	0.69	0.87
	P		0.81	0.41	0.77	0.82	0.87	0.94
	K		0.23	0.02	0.15	0.21	0.30	0.69

doi: 10.17221/417/2017-PSE

Table 2. Internal efficiency (kg/kg) and reciprocal internal efficiency (kg/t) of nitrogen (N), phosphorus (P) and potassium (K) for maize

Parameter		Mean	Minimum	25% quartile	Median	75% quartile	Maximum
Internal efficiency	N	54.3	19.4	44.0	51.5	61.5	160.2
	P	251.5	123.8	209.0	243.9	282.6	579.2
	K	78.2	14.6	52.6	70.5	94.8	215.7
Reciprocal internal efficiency	N	19.8	6.2	16.3	19.4	22.7	51.4
	P	4.2	1.7	3.5	4.1	4.8	8.1
	K	15.4	4.6	10.5	14.2	19.0	68.7

above-ground plant was distributed in grain, and the remaining was distributed in straw. Remarkably, the K stored in straw was relatively high, approximately 70.1% higher than that stored in grain.

Reciprocal internal efficiency was defined as the amount of a nutrient in the plant needed to produce 1000 kg grain. For all maize data, the average IEs were 54.3 kg, 251.5 kg, and 78.2 kg grain per kg N, P and K, respectively. In other words, to produce 1000 kg maize yield, the average N, P and K requirements were 19.8 kg N, 4.2 kg P and 15.4 kg K, respectively (Table 2).

Selection of data for adjustment of the QUEFTS model. There was a tremendous variation range in the database, which could be due to the wide ranges of production areas and environmental conditions. Not all data were suitable for the QUEFTS model.

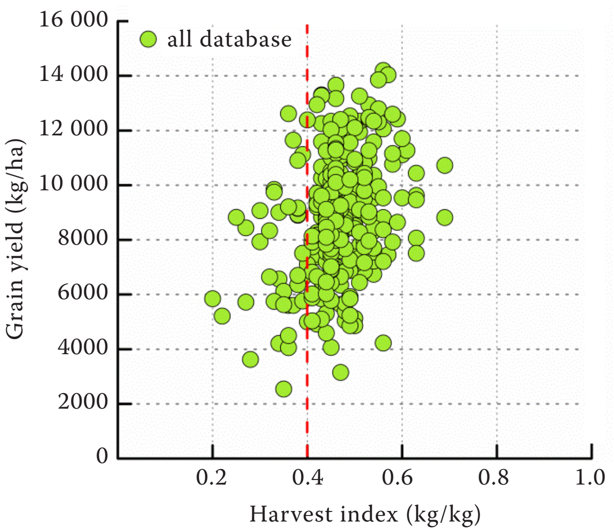

Figure 4. Distribution of grain yield and harvest index of maize. The red line represents a screening line to exclude outliers in the database

Harvest index was an important indicator used for screening the database in QUEFTS model. Across the maize database, the average harvest index was 0.46, ranging from 0.2 to 0.69 (Table 1). Most of the HIs in the study were between 0.4 and 0.6, and those < 0.4 were considered as anomalies in the dataset; they possibly suffered from impact of biotic or abiotic factors. In order to guarantee the accuracy of calculation, a lower HI boundary was used to exclude the data with HI < 0.4; about 13% extreme values of all data were excluded and 262 groups of maize data remained (yield ranged from 3150 to 14 196 kg/ha) (Figure 4).

Parameters for the QUEFTS model. The prerequisite of using the QUEFTS model was to calculate the slopes of two borderlines of the maximum accumulation (*a*) and dilution (*d*) of N, P and K. Thus, three sets of constants *a* and *d* values were calculated by excluding the upper and lower 2.5 (set I), 5 (set II), and 7.5 (set III) percentiles of all IEs data of a particular nutrient (Table 3).

Here, the yield potential of maize was fixed as 14 000 kg/ha as an example (Figure 5). The curves of the balanced nutrient requirements simulated

Table 3. Coefficients of maximum accumulation (*a*) and dilution (*d*) of nitrogen (N), phosphorus (P) and potassium (K) in the above-ground dry matter for maize

Nutrient	Set I		Set II		Set III	
	a (2.5^{th})	*d* (97.5^{th})	*a* (5^{th})	*d* (95.5^{th})	*a* (7.5^{th})	*d* (92.5^{th})
N	34.1	93.3	36.2	84.2	38.4	77.7
P	151.8	410.9	167.3	372.3	179	360
K	40.2	184.4	41.9	161.8	44.3	142.9

doi: 10.17221/417/2017-PSE

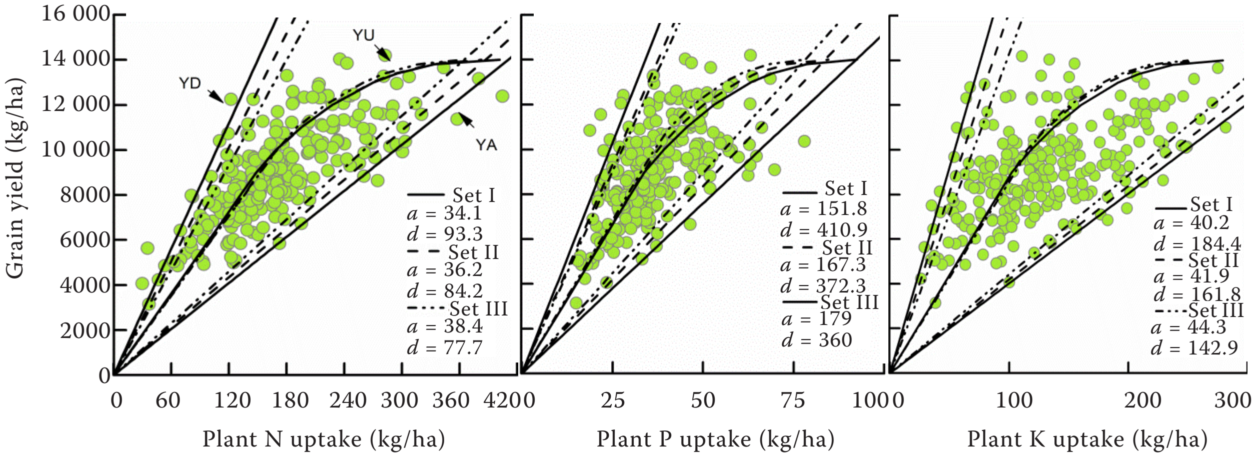

Figure 5. Balanced nutrient requirements of nitrogen (N), phosphorus (P) and potassium (K) at different sets simulated by the QUEFTS model. Yield potential was set at 14 000 kg/ha

by the QUEFTS model were similar for the three sets (Figure 5). Considering that Set I contained a broad range of variables, it is presumed that set I could be used as borderlines slope set in QUEFTS for maize. The constant *a* and *d* of N, P and K in Set I were 34.1 and 93.3 kg grain per kg N, 151.8 and 410.9 kg grain per kg P, and 40.2 and 184.4 kg grain per kg K, respectively.

Estimating balanced nutrient uptake at different yield potential. Using the QUEFTS model simulated a linear-parabolic-plateau curve for balanced N, P and K requirements at different yield potential levels (10 000 to 14 000 kg/ha) (Figure 6). For the linear part, the balanced nutrient requirements showed a linear increase until the yield target reached approximately 60–70% of the yield potential, and 16.7 kg N, 3.8 kg P and 11.4 kg K would be needed to produce 1000 kg grain yield. Correspondingly, the IE values for N, P and K were 60.0 kg/kg for N, 256.7 kg/kg for P, 88.0 kg/kg for K. The N:P:K ratios were 4.69:1:3.02.

When the yield target was gradually reached up to the yield potential, the curve of crop nutrient uptake showed a plateau level (Figure 6). Specifically, when crop yield levels reach more than 60–70% of the site yield potential, crop requires greater amounts of nutrients per unit increase in grain yield; therefore, greater attention in inputting appropriate nutrients at grain filling period is to be paid. This study is important for many provinces in China, not only as a reference but it also provides a promising method for estimating the nutrient requirements of other crops in different regions.

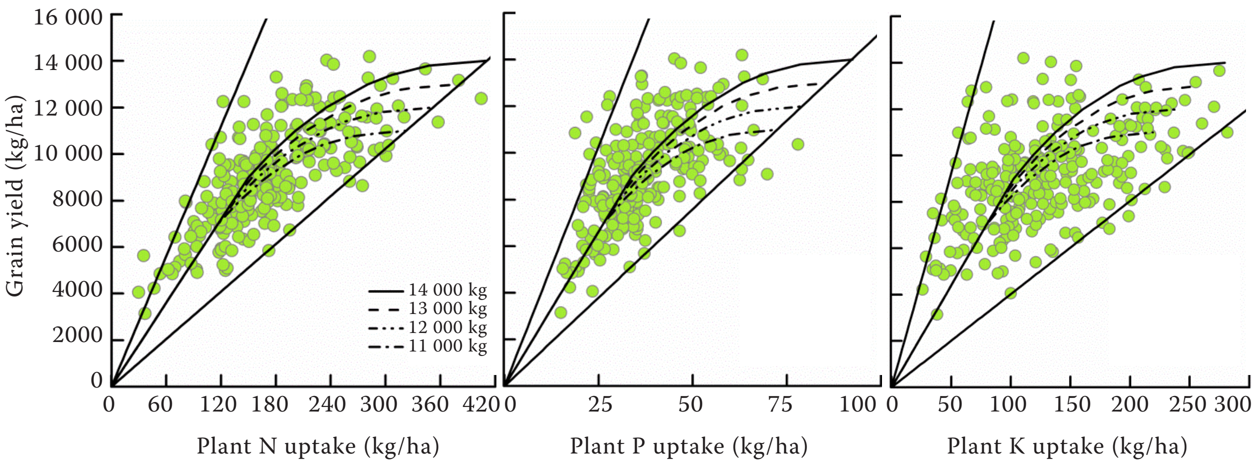

Figure 6. Balanced nitrogen (N), phosphorus (P) and potassium (K) uptake at different yield potential simulated by the QUEFTS model for maize in the Northeast China

doi: 10.17221/417/2017-PSE

REFERENCES

Bao S.D. (2000): Soil and Agricultural Chemical Analysis. 3rd Edition. Beijing, China Agriculture Press. (In Chinese)

Buresh R.J., Pampolino M.F., Witt C. (2010): Field-specific potassium and phosphorus balances and fertilizer requirements for irrigated rice-based cropping systems. Plant and Soil, 335: 35–64.

Cui Z.L., Chen X.P., Zhang F.S. (2010): Current nitrogen management status and measures to improve the intensive wheat-maize system in China. Ambio, 39: 376–384.

Dai J., Wang Z.H., Li F.C., He G., Wang S., Li Q., Cao H.B., Luo L.C., Zan Y.L., Meng X.Y., Zhang W.W., Wang R.H., Malhi S.S. (2015): Optimizing nitrogen input by balancing winter wheat yield and residual nitrate-N in soil in a long-term dryland field experiment in the Loess Plateau of China. Field Crops Research, 181: 32–41.

Das D.K., Maiti D., Pathak H. (2009): Site-specific nutrient management in rice in Eastern India using a modeling approach. Nutrient Cycling in Agroecosystems, 83: 85–94.

Dobermann A., Cassman K.G., Mamaril C.P., Sheehy J.E. (1998): Management of phosphorus, potassium, and sulfur in intensive, irrigated lowland rice. Field Crops Research, 56: 113–138.

FAO (2011): FAOSTAT Database-Agricultural Production. Rome, FAO.

Fedoroff N.V., Battisti D.S., Beachy R.N., Cooper P.J.M., Fischhoff D.A., Hodges C.N., Knauf V.C., Lobell D., Mazur B.J., Molden D., Reynolds M.P., Ronald P.C., Rosegrant M.W., Sanchez P.A., Vonshak A., Zhu J.-K. (2010): Radically rethinking agriculture for the 21st century. Science, 327: 833–834.

Grassini P., Eskridge K.M., Cassman K.G. (2013): Distinguishing between yield advances and yield plateaus in historical crop production trends. Nature Communications, 4: 2918.

Huang S.-W., Jin J.-Y., Yang L.-P., Bai Y.-L. (2006): Spatial variability of soil nutrients and influencing factors in a vegetable production area of Hebei province in China. Nutrient Cycling in Agroecosystems, 75: 201–212.

Li S.T., Jin J.Y., Zhu J.H. (2011): Characteristics of nutrient input/output and nutrient balance in different regions of China. Scientia Agricultura Sinica, 44: 4207–4229. (In Chinese)

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

Ma Q.H., Wang X., Li H.B., Li H.G., Zhang F.S., Rengel Z., Shen J.B. (2015): Comparing localized application of different N fertilizer species on maize grain yield and agronomic N-use efficiency on a calcareous soil. Field Crops Research, 180: 72–79.

Ray D.K., Ramankutty N., Mueller N.D., West P.C., Foley W.J.A. (2012): Recent patterns of crop yield growth and stagnation. Nature Communications, 3: 187–190.

Sai'dou A., Janssen B.H., Temminghoff E.J.M. (2003): Effects of soil properties, mulch and NPK fertilizer on maize yields and nutrient budgets on ferralitic soils in southern Benin. Agriculture, Ecosystems and Environment, 100: 265–273.

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.

Tilman D., Balzer C., Hill J., Befort B.L. (2011): Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences of the United States of America, 108: 20260–20264.

Wang Y., Feng G.Z., Yan L., Gao Q., Song L.X., Liu Z.G., Fang J. (2016): Present fertilization effect and fertilizer use efficiency of maize in Jilin Province. Journal of Plant Nutrition and Fertilizer, 22: 1441–1448. (In Chinese)

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.

Wu L.-Q., Ma W.-Q., Zhang C.-C., Wu L., Zhang W.-F., Jiang R.-F., Zhang F.-S., Cui Z.-L., Chen X.-P. (2013): Current potassium-management status and grain-yield response of Chinese maize to potassium application. Journal of Plant Nutrition and Soil Scienc, 176: 441–449.

Xu X.P., Ping H., Pampolino M.F., Chuan L.M., Johnston A.M., Qiu S.J., Zhao S.C., Wei Z. (2013): Nutrient requirements for maize in China based on QUEFTS analysis. Field Crops Research, 150: 115–125.

Yang F.Q., Xu X.P., Wang W., Ma J.C., Wei D., He P., Pampolino M.F., Johnston A.M. (2017): Estimating nutrient uptake requirements for soybean using QUEFTS model in China. PLosOne. 12: e0177509.

Zhao R.-F., Chen X.-P., Zhang F.-S., Zhang H.L., Schroder J., Romheld V. (2006): Fertilization and nitrogen balance in a wheat-maize rotation system in North China. Agronomy Journal, 98: 938–945.

Received on July 5, 2017
Accepted on October 19, 2017
Published online on November 6, 2017