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Establishment and Validation of Nutrient Expert System for Radish Fertilization Management in China

Jiajia Zhang, Wencheng Ding, Ping He,* Xinpeng Xu, Tanveer Abbas,
Sami Ullah, Chao Ai, Mingyue Li, Rongzong Cui, Chongwei Jin, and Wei Zhou*

ABSTRACT

Imbalanced nutrient application has resulted in low productivity and nutrient use efficiency (NUE) for radish (*Raphanus sativus* L.) production in China. This study aims to introduce a science-based, cost-effective, and reliable nutrient management approach to resolve the problem. A radish database from 247 published and unpublished studies with on-farm experiments from 2000 to 2017 in the main radish-producing regions in China was established to develop Nutrient Expert (NE) system for radish nutrient management and field experiments were conducted to evaluate its feasibility. The relationships among indigenous soil nutrient supply, yield response (YR), agronomic efficiency (AE), and relative yield were investigated for the establishment of NE system. Results showed that the average indigenous supply of N, P, and K in soil was 118.7, 28.2, and 208.8 kg ha^{-1}, respectively. The mean YR of radish to N, P, and K was 17.7, 10.4, and 10.3 t ha^{-1}, respectively; while the AE of them was 104.7, 105.0, and 69.5 kg kg^{-1}. Significantly negative exponential relationship between YR and indigenous nutrient supply and linear correlation between YR and relative yield were observed. Results demonstrated a quadratic curve relationship between YR and AE. The NE system for radish was developed based on YR and AE, and field experiments validified that NE system significantly enhanced fleshy root yield of radish, profitability, and NUE over those obtained under farmers' practices (FP). The NE system for radish demonstrated a promising method and will assist Chinese radish growers in achieving effective fertilizer use and higher yield goals.

Core Ideas

- Soil indigenous nutrient supply, yield response, and agronomic efficiency were analyzed in radish-producing regions.
- The relationships among yield response, indigenous nutrient supply, and agronomic efficiency were determined.
- Nutrient Expert for radish was first established based on yield response and agronomic efficiency.

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Radish is an important member of the Cruciferae family and an important vegetable worldwide due to its wide adaptive abilities and abundant nutritional content (Curtis, 2003). In China, radish is the second most cultivated vegetable. As of the end of 2016, the radish planting area in China was 1.2 million ha, and the annual total production was 44.6 Tg of fresh tuberous roots. These amounts corresponded to 40% of the global land area used for radish production and 47% of the worldwide radish yield, respectively (FAO, 2017). Fertilizer application is crucial for high radish yield and good fleshy root quality. However, chemical fertilizer is generally overapplied by radish growers because of the absence of effective soil testing and the lack of environment protection awareness (Zhu and Chen, 2002; Huang et al., 2006). In some vegetable cultivation regions of northern and southern China, single-season nitrogenous fertilizer input exceeds 300 and 500 kg N ha^{-1}, respectively, which is almost twice the need of most vegetable crops (Shi et al., 2009; Huang et al., 2017). This high N fertilizer application has resulted in low N use efficiency with values of 18 and 33% in southern and northern China, respectively (Song et al., 2009; Min et al., 2011). Excessive fertilization, especially with N fertilizer, not only reduces vegetable quality but also leads to poor economic returns, inefficiency in nutrient use, and global environmental problems such as eutrophication, greenhouse gas emissions, and groundwater pollution (Zhang et al., 2013; Huang et al., 2017). Thus, there is an urgent need to develop a science-based fertilizer recommendation for radish in vegetable production systems that aims to increase NUE while minimizing harmful agricultural impacts on the environment.

Some soil- and plant-based nutrient management practices have been used to enhance radish yield and NUE. Examples include leaf color charts and chlorophyll meters, which generally

J. Zhang, W. Ding, P. He, X. Xu, T. Abbas, S. Ullah, C. Ai, 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 (CAAS), Beijing 100081, China; P. He, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China; M. Li, Tianjin Institute of Agricultural Resources and Environment, Tianjin 300192, China; R. Cui, Institute of Agricultural Resources and Environment, Shandong Academy of Agricultural Sciences, Jinan 250100, China; C. Jin, The Ministerial Key Lab. of Remediation of Pollution Environment and Eco-health, Zhejiang Univ., Hangzhou 310029, China. Received 2 Jan. 2019. Accepted 21 Mar. 2019. *Corresponding authors (heping02@caas.cn, zhouwei02@caas.cn)

Abbreviations: AEN, agronomic efficiency of nitrogen; FP, farmers' practices; IKS, indigenous soil potassium supply; INS, indigenous soil nitrogen supply; IPS, indigenous soil phosphorus supply; NE, Nutrient Expert; NUE, nutrient use efficiency; PFPN, partial factor productivity of nitrogen; REN, recovery efficiency of nitrogen; YR, yield response.

provide real-time guidance for the topdressing application of N fertilizer for crops (Westerveld, 2004; Quadros et al., 2010). Soil testing has been encouraged and used to develop nutrient recommendations in China (Bai and Yang, 2006; He et al., 2009; Song and Yi, 2011). However, numerous challenges are still linked with this method, including the collection and identification of suitable analytical methods for representative soil samples as well as the establishment of a good correlation and calibration between soil testing data and yield response (He et al., 2012). Additionally, radish cultivation is generally accessible to people having a few hectares of land and limited financial resources; among these individuals, soil testing is considered a time-consuming and expensive tool.

A science-based, cost-effective, and site-specific nutrient management system is required that can be readily adopted by local farmers with limited resources. International Plant Nutrition Institute (IPNI) developed a new nutrient decision support system, NE for hybrid maize, with the purpose of developing fertilizers recommendations to local farmers based on scientific knowledge provided by advisors (Pampolino et al., 2012). The NE system makes fertilizer recommendations based on YR and AE, and adopts the principles of site-specific nutrient management (SSNM) (Dobermann et al., 2002) and the quantitative evaluation of the fertility of tropical soils (QUEFTS) model to evaluate the optimum requirements of the nutrient for crops (Janssen et al., 1990; Smaling and Janssen, 1993). The YR is related to indigenous soil nutrient supply which originates from biological N fixation, atmosphere deposition, fertilizer and crop residues, and irrigation water (Dobermann et al., 2003). This approach considers the indigenous soil nutrient supply which is characterized by the yield or the whole amount of a specific nutrient uptake from the omission plots (Dobermann et al., 2003), thus solving the problem of soil N supply that has not yet been adequately addressed (He et al., 2012). The NE system makes full use of the indigenous soil nutrient supply to avoid excessive or deficient nutrients absorbed by crops while maintaining soil fertility (Pampolino et al., 2012). In all other nutrient management systems, nutrient interactions are neglected, whereas in the NE system, plant nutrient interactions are considered, which represents a unique feature of the NE system. In addition, this system advocates 4R nutrient stewardship (to apply fertilizer with the right source, at the right rate, right time, and right place) (Johnston and Bruulsema, 2014). Therefore, the NE system is considered an alternative method for small-holder farmers who cannot afford soil testing or when soil testing is unavailable.

Until now, the application of the NE system has been successfully used in wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), and rice (*Oryza sativa* L.) crops in some Asian and African countries with smallholders (i.e., China, Indonesia, and Philippines) (Pampolino et al., 2012; Chuan et al., 2013; Xu et al., 2014, 2017). However, attempts to develop NE system for radish crops in vegetable systems has never been tried. Therefore, it is imperative to develop a NE system for site-specific and dynamic nutrient management to satisfy the demands for both high NUE and environmental-friendly practices in radish production in China. Successful applications of a NE system on cereal crops have provided a good theoretical and practical basis for the establishment of the NE system for radish. However, there have been limited systematic analyses of YR, AE, and soil indigenous nutrient supply across multiple sites/years for the radish production areas of China. We hypothesized that there are strong correlations among these parameters on radish, based on which we can successfully establish the NE system for radish fertilization management in China. Given that this comprehensive study was conducted with the purposes of (i) determining soil indigenous nutrient supply, YR, and AE in radish-growing areas in China; (ii) investigating the associations among them; and (iii) developing and validating the NE system for radish.

MATERIALS AND METHODS

Data Collection

The radish datasets in this study were compiled from published articles (China National Knowledge Infrastructure, 2000–2017) available in the China Knowledge Resource Integrated Database (www.cnki.net) and unpublished studies conducted by the IPNI China Program and our group. and the datasets keep updating over time (data from field validation experiments described in the following Field Validation section was also supplemented to the latest datasets). The database was concerned with the main radish-growing areas and included the following variables (Fig. 1, Table 1): (i) climate (cool temperate, temperate, subtropical, and tropical), (ii) plant type according to season (spring radish, summer radish, autumn radish, and winter radish), and cropping systems (broccoli [*Brassica oleracea*]–spring radish, potato [*Solanum tuberosum* L.] –autumn radish, cabbage–autumn radish, tomato [*Lycopersicon esculentum* Mill.]–autumn radish, and monocropped radish); and (iii) nutrient management practices, including treatment type (current FP, optimum practice treatment, nutrient omission treatments based on optimum practice treatment and FP, and treatments with different fertilizer rates).

Parameterization of the Nutrient Expert System

According to farmers' actual yield and site characteristics, maximum attainable yield (Ymax) is determined in the NE system for a crop growing environmental condition to estimate the attainable yield (Ya). Ya is determined by field experiments under the best management with sufficient nutrient supply, while Ymax can be obtained from a suitable field experiment with no management limitation. In the NE system, the difference of maximum yield between field experiments and FP is detected to determine the increase of the yield by considering the level of risk. A decision rule was employed in the NE system to measure Ya through Ymax, and the risk level was set as low, medium, or high with the consideration of the probabilities of flood or drought and the problems of soil (e.g., degradation, salinity, etc.). It was assumed that Ya is lower than Ymax in high risk condition while Ya is equal to Ymax in the case of low risk, where the minimum Ya is consistent with the farmers' yield (Pampolino et al., 2012).

Soil fertility level or the indigenous supply of nutrient in soil can be estimated using YR (the yield difference between plots with sufficient N, P, and K nutrients and those lacking one of these nutrients) and a lower YR indicates higher indigenous soil nutrient supply. However, when the YR is unavailable, it can be estimated using the relative yield (the ratio of nutrient-limited yield to Ya). The nutrient-limited yield for a certain Ya and soil fertility level was estimated with the 25th percentile, 50th percentile,

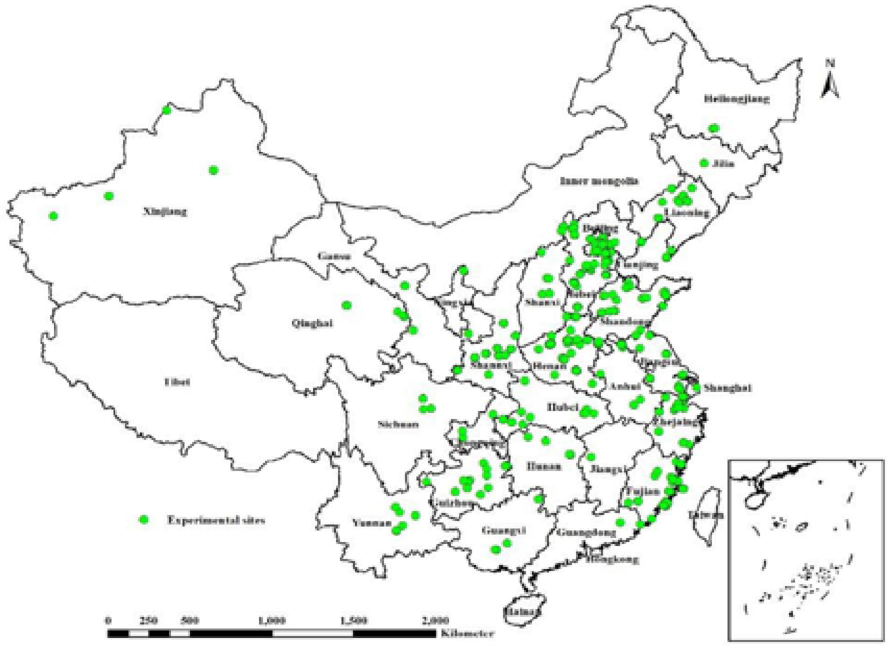

Fig. 1. Geographical distribution of radish experimental sites (2000–2017) in China (data from radish datasets).

Table 1. Climate characteristics of the experimental sites in radish-producing regions in China.

Province	Climate type	Radish season	No.†	Annual precipitation	Latitude	Longitude
				mm	°N	°E
Jilin	Cool temperate	Autumn	5	400–1000	43.73–43.82	125.09–125.37
Liaoning		Autumn	43	450–1000	38.84–42.71	121.17–124.04
Heilongjiang		Autumn	15	400–650	45.68–45.70	126.62–126.77
Shannxi	Temperate	Summer and Autumn	82	200–600	33.06–35.99	106.16–110.15
Ningxia		Autumn	4	200–600	39.08	106.67
Gansu		Autumn	34	100–300	35.44–38.18	102.50–106.95
Xinjiang		Autumn	16	100–500	39.25–46.72	76.80–87.56
Qinghai		Autumn	39	200–400	36.41–36.93	98.48–102.54
Beijing	Temperate	Autumn	119	550–650	34.65–40.46	112.50–117.09
Tianjin		Spring and Autumn	202	350–750	34.48–40.12	112.59–117.77
Shanxi		Autumn	12	350–700	37.52–39.95	112.17–112.67
Shandong		Spring and Autumn	226	550–900	34.65–37.13	115.00–120.76
Henan		Autumn	256	500–900	32.16–40.49	111.65–116.94
Hebei		Spring and Autumn	314	350–500	36.13–41.39	113.75–119.60
Anhui	Temperate subtropical	Autumn and Winter	31	700–1400	30.69–34.06	115.59–117.98
Hubei		Autumn	82	750–1500	30.11–32.61	109.04–114.90
Hunan		Autumn	45	900–1700	28.15–29.37	110.58–113.17
Jiangsu		Autumn	60	800–1200	31.22–34.55	117.24–120.89
Jiangxi		Autumn	3	1200–1900	27.92	114.44
Shanghai		Autumn	5	1000–1500	31.19	121.73
Zhejiang		Spring and Autumn	114	980–2000	27.98–30.78	118.88–122.53
Chongqing	Subtropical	Autumn	23	750–1400	29.44–30.76	106.42–108.39
Guizhou		Summer and Autumn	106	1100–1400	26.10–27.93	104.17–109.16
Yunnan		Autumn	36	600–2000	23.95–25.35	102.30–103.51
Sichuan		Autumn	31	1000–1300	31.09–31.70	103.90–104.42
Guangxi	Tropical	Autumn	33	1200–2000	22.81–25.70	108.25–111.01
Guangdong		Autumn	19	1500–2000	23.71–23.94	115.78–116.94
Fujian		Spring and Autumn	192	1400–2000	23.96–30.36	116.41–120.46

† No. is the number of samples (data from radish datasets).

and 75th percentile of all relative yield data as coefficients. The 25th percentile, 50th percentile, and 75th percentile represent the soil fertility of low, average, and high, respectively (Pampolino et al., 2012). Soil characteristics (e.g., soil texture, color, and organic matter content), historical organic materials use (if available) and apparent balance of P and K from the previous crop can be used to determine indigenous soil N, P, and K supply (INS, IPS, and IKS) classes. The P and K balance is the inputs (from both organic and inorganic sources) minus the output. If soil P and K test values are available, they are combined with the P and K balance to determine the classes of IPS and IKS. The NE system uses the INS classes and apparent nutrient balance to determine the soil P and K levels if soil test values are unavailable.

The AE represents the increase of the yield when one unit of N, P_2O_5, or K_2O is applied. In the NE system, the optimum nutrient management practice treatments collected from multiple sites in different ecological regions were used to calculate YR and thereby obtain a reasonable AE.

Description of the Nutrient Expert System

The NE system is a user-friendly computer-supported program and the principles of nutrient management were developed to consolidate the knowledge intensive and complex information into easily grasped software. It can rapidly generate fertilizer recommendations through given site information for individual farmers with or without soil testing. The YR and AE are key components for fertilizer application. The target AE of applied N and the expected YR are the bases for determining N requirements, whereas for P and K fertilizer recommendations, their internal efficiency combined with estimations of *Ya*, balance, and YR are all important in the NE system for a specific crop (Buresh and Witt, 2007; Pampolino et al., 2011). The P and K balances are calculated by considering the residual effects of previously applied fertilizers as well as crop residues before the application of P and K fertilizers to avoid excessive nutrient additions in the soil.

The NE system requires information including FP on crop management and fertilizer application for the previous season that can be easily obtained by farmers based on the investigation before fertilization. A few questions about growing environments include water availability (flooding and drought incidence), problem soils if any like saline and acidity soils, are used to evaluate *Ya* based on low, medium, and high risk analysis, and soil fertility indicators like soil texture and soil color are used in combination with the *Ya* evaluate YR based on big database (Pampolino et al., 2012). The database of site characteristics and agronomic parameters from field experiments is used to develop decision rules for evaluating the indigenous soil nutrient supply based on locally-available information; thus, fertilizer recommendations can be developed even without experimental data on nutrient omission. The NE system is not specifically aimed at reducing or increasing fertilizer application rates, but involving the dynamic nutrients management to optimize the nutrients supply and demand to balance soil nutrients and giving nutrient management strategies that are tailored to the specific field using 4R nutrient stewardship.

Field Validation

Field validation experiments of fertilizer recommendations for radish cultivation based on the NE system were conducted on 34 farmers' fields in the main cultivation areas in China.

Table 2. Fertilizer application rates.

Province	Treatment	Fertilizer application rate N	P_2O_5	K_2O
		kg ha^{-1}		
Tianjin	NE†	161 (145–189)‡	97 (79–119)	209 (140–279)
	FP§	243 (144–366)	193 (117–294)	291 (215–404)
Shandong	NE	162 (143–186)	91 (54–106)	213 (176–248)
	FP	222 (171–247)	155 (131–179)	207 (171–227)
Beijing	NE	163 (160–170)	90 (62–107)	224 (161–246)
	FP	280 (247–293)	219 (170–233)	248 (190–263)
Hebei	NE	150	100	180
	FP	113	113	113
Zhejiang	NE	150	100	180
	FP	218 (203–234)	165 (150–180)	148 (143–153)

† NE, fertilizer application based on the Nutrient Expert for Radish decision support system.

‡ Data in parentheses indicate the fertilizer application range (data from field validation experiments).

§ FP, fertilizer application based on farmers' practices.

The experimental sites were distributed among Tianjin (10 fields) and Shandong (11 fields) (from autumn 2016 to autumn 2018), Hebei (3 fields) and Zhejiang (2 fields) (from autumn 2016 to autumn 2017), and Beijing (8 fields) (from spring 2018 to autumn 2018). Radish is a popular local vegetable that is cultivated in open fields during spring and autumn at these sites (Wang and He, 2005). Spring radish was grown from early or mid-April to mid-June. Autumn radish was grown from early or mid-August to late October or early November. For treatments allocation at each experimental site, a randomized complete block design (RCBD) with three replicates was used. At each experimental site, five treatments were applied, including FP, fertilization based on current farmers' management practices without involvement of any research group; NE, fertilization as recommended by the NE system; and the omission of N, P, and K from the NE treatment. Nutrient use efficiency was calculated from the data of omission plots.

The plot size was 20 to 30 m^2, and each plot included five rows for all experiments. The planting density was 50 by 30 cm (row spacing and plant spacing) in Tianjin, Hebei, and Beijing, 65 by 20 cm in Shandong, and 15 by 15 cm in Zhejiang. The total required amount of P fertilizer according to the NE system was added as the basal dose, whereas the application of N and K was split three times at critical growth stages. First, the basal dose of N and K fertilizers was applied and then second and third doses were applied as topdressing at the rosette stage and the fleshy root-expanding stage, respectively. With regards to FP treatment, the application of P and K was performed as basal fertilizers before radish sowing and N was normally applied twice: basal fertilizer, topdressing was performed by hole application between plants at the fleshy root expanding stage. All basal fertilizers were first soil surface-broadcasted and then thoroughly mixed into the soil with a cultivator presowing. The variety of N, P, and K fertilizers applied was urea (46% N), single superphosphate (12% P_2O_5), and potassium sulfate (50% K_2O), respectively. For the field validation experiments, the fertilizer rates are presented in Table 2. Irrigation; weeds, pests, and diseases control; and other cultural practices followed local best management practices, and the crops were protected from biotic and abiotic stresses.

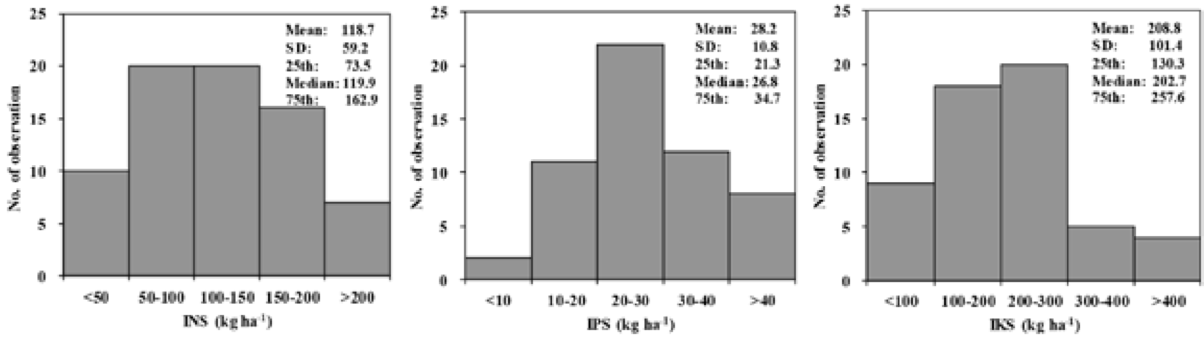

Fig. 2. Frequency distributions of indigenous N, P, and K supplies for radish. INS, IPS, and IKS indicate indigenous nitrogen, phosphorus, and potassium supply, respectively (data from radish datasets).

At harvest, the middle three rows of each plot were used for plant sampling and harvesting. The crop was harvested manually, and the total weights of fleshy roots and leaves were measured separately. Dry matter weights of the harvested fleshy root and leaf samples were determined after oven-drying at 70°C. Subsamples of fleshy roots and leaves were taken to determine N concentrations using the Kjeldahl method. Plant N uptake was measured by multiplying the dry biomass (separated into fleshy roots and leaves) with N concentration. The fleshy root yield for each plot was expressed in fresh weight.

Measures of N use efficiency includes recovery efficiency (RE), AE, and partial factor productivity (PFP) of N, which were calculated according to Zhang et al. (2018):

$$\mathrm{RE}_N = \frac{\mathrm{U}-\mathrm{U}_0}{\mathrm{N}} \times 100 \quad [1]$$

$$\mathrm{AE}_N = \frac{\mathrm{Y}-\mathrm{Y}_0}{\mathrm{N}} \quad [2]$$

$$\mathrm{PFP}_N = \frac{\mathrm{Y}}{\mathrm{N}} \quad [3]$$

where U and U_0 are the N uptake amount by the crops (kg ha^{-1}) from N-treated and untreated plots, respectively; Y and Y_0 represent fleshy root yield (kg ha^{-1}) from N-treated and untreated plots, respectively; and N is the input of fertilizer N (kg ha^{-1}).

U.S. dollars was used as standard currency for economic calculations:

$$\text{Net return} = P_R Y_R - P_N F_N - P_P F_P - P_K F_K \quad [4]$$

where net return equals the adjusted gross return from which fertilizer cost was subtracted (US\$ ha^{-1}); P_R is the price of radish fleshy root; P_N, P_P, and P_K are the prices of N, P, and K fertilizers, respectively; Y_R is fleshy root yield of radish (kg ha^{-1}); and F_N, F_P, and F_K are the amounts of applied N, P_2O_5, and K_2O (kg ha^{-1}), respectively.

Statistical Analysis

The PROC GLM procedure of SAS 9.3 (SAS Institute, Inc., Cary, NC) was used to analyze the effects of different treatments on radish yield, net return, and N use efficiency using the general linear model for all sites. The field experiments were performed over different intervals in certain provinces; therefore, all data for the different provinces were presented. While comparing each of the variables between NE and FP treatments for the same province, the treatments were treated as a fixed effect, and the field experiment time period was treated as a random effect. The differences between the NE and FP treatment were determined using Duncan's multiple range test at the 0.05 level.

RESULTS

Indigenous Nutrient Supply

The average supplies of INS, IPS, and IKS were 118.7, 28.2, and 208.8 kg ha^{-1} (Fig. 2), respectively, with ranges from 11.3 to 258.1, 6.9 to 54.2, and 51.1 to 461.7 kg ha^{-1}, respectively. The frequency distribution results of indigenous nutrient supply showed that 76.7% of INS of all experimental observations were between 50 and 200 kg ha^{-1}. For IPS and IKS, approximately 81.8 and 67.9% of all observations were within 10 to 40 and 100 to 300 kg ha^{-1}, respectively.

Yield Response and Relative Yield

The mean YR of radish to N, P, and K was 17.7, 10.4, and 10.3 t ha^{-1}, with ranges of 0 to 46, 0 to 32, and 0 to 38 t ha^{-1}, respectively (Fig. 3). The YR to N, P, and K application below 30, 20, and 20 t ha^{-1} accounted for 81.3, 90.5, and 88.2% of total observations, respectively. The high YR to N values showed that N was the most limiting component of radish yield among all nutrients. Nevertheless, the results also suggested that adding appropriate amounts of P and K fertilizers was important.

A significant negative linear correlation was obtained between YR and relative yield ($P < 0.0001$, Fig. 4), and the correlation coefficients (R^2) were 0.78, 0.80, and 0.75 for N, P, and K, respectively. On average, the values of N relative yield (GY0N/Ya), P relative yield (GY0P/Ya), and K relative yield (GY0K/Ya) were 0.73, 0.86, and 0.85 (Fig. 5), respectively, with ranges from 0.23 to 1.0, 0.39 to 1.0, and 0.35 to 1.0, respectively, indicating that N was the nutrient that most strongly limited yield. Approximately 30.0% of the relative yield were within 0.3 to 0.7 and 66.4% were between 0.7 and 1.0. Values of relative yield for P and K approximately 77.4 and 91.3% of all experimental observations were within 0.8 to 1.0 and 0.7 to 1.0, respectively.

Agronomic Efficiency

The mean values of AEN, AEP, and AEK were 104.7, 105.0, and 69.5 kg kg^{-1}, with ranges of 0 to 325, 0 to 410, and 0 to 250 kg kg^{-1}, respectively (Fig. 6). The AEN values less than 100 kg kg^{-1} accounted for 53.3% of the total experimental observations; those between 100 and 200 kg kg^{-1} accounted for

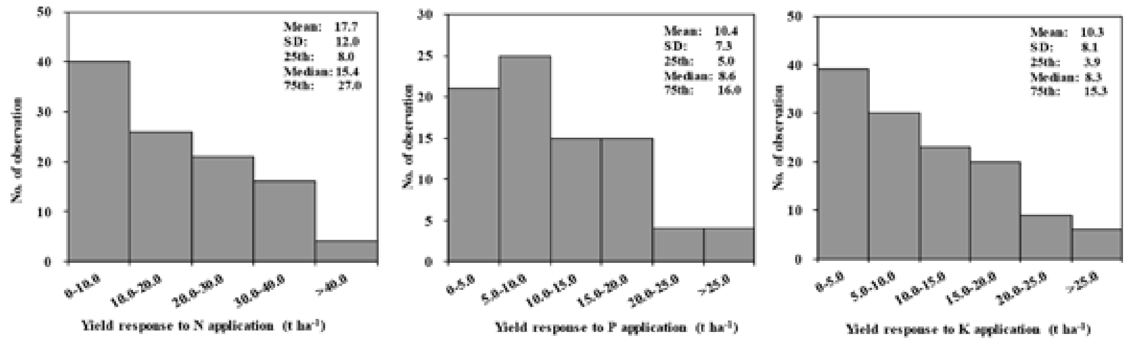

Fig. 3. Frequency distributions of yield response to applied N, P, and K fertilizer for radish (data from radish datasets).

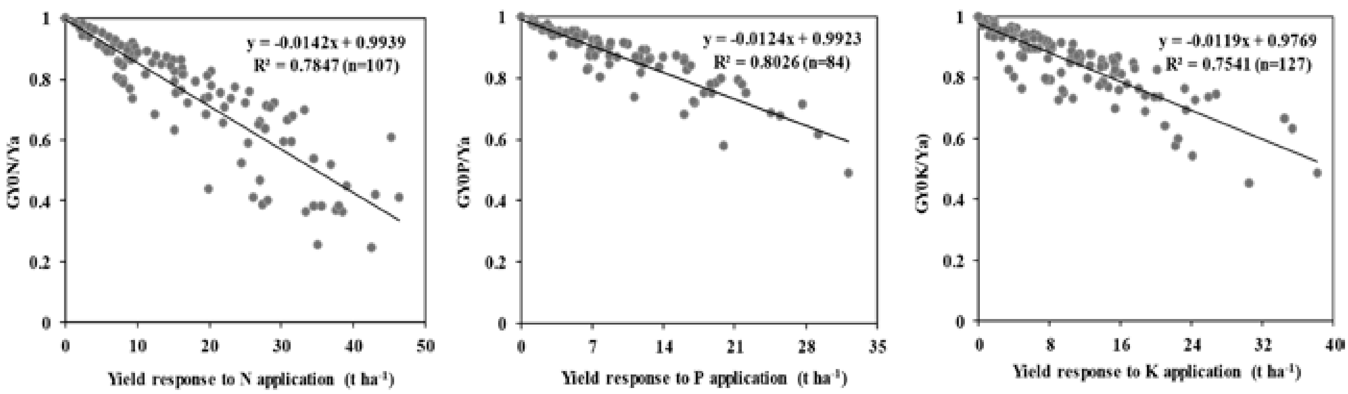

Fig. 4. Relationship between yield response and relative yield for radish. The relative yields GY0N/Ya, GY0P/Ya, and GY0K/Ya are the ratios of nutrient-limited yield to attainable yield for nitrogen, phosphorus, and potassium, respectively (data from radish datasets).

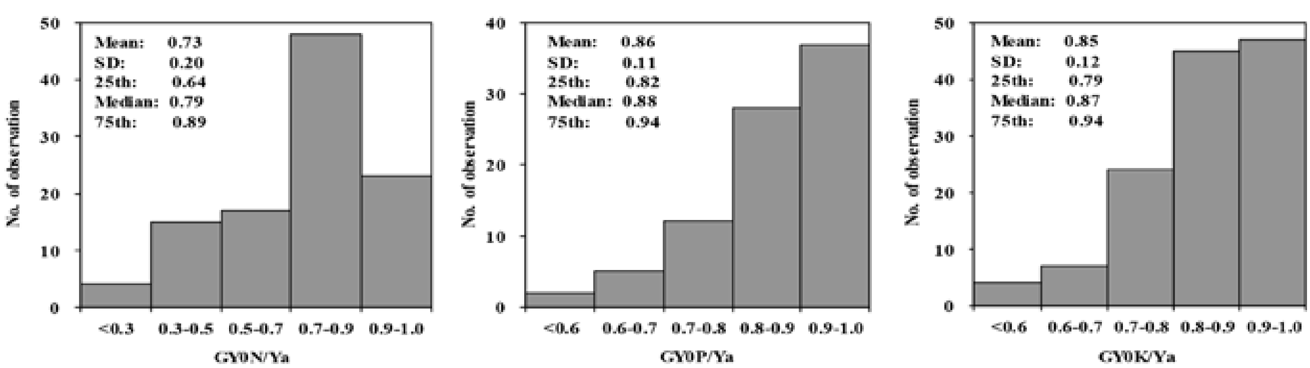

Fig. 5. Frequency distributions of relative yield to N, P, and K fertilizer for radish. The relative yields GY0N/Ya, GY0P/Ya, and GY0K/Ya are the ratios of nutrient-limited yield to attainable yield for nitrogen, phosphorus, and potassium, respectively (data from radish datasets).

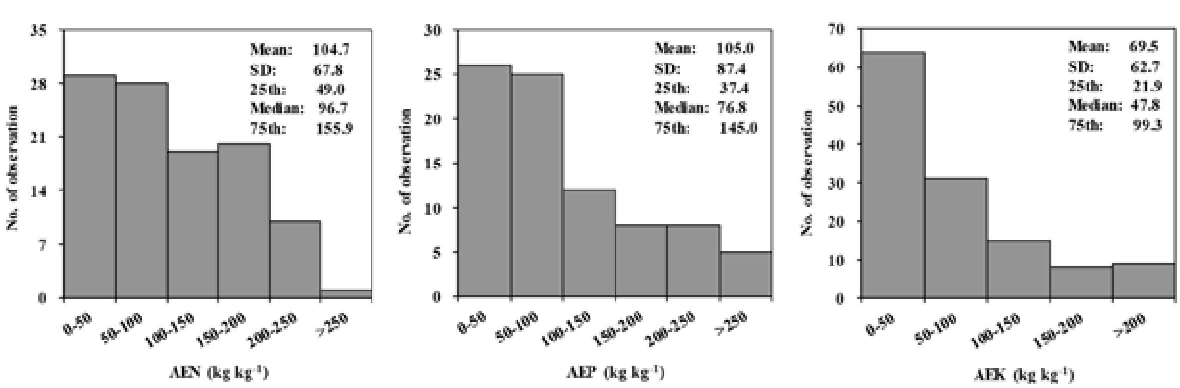

Fig. 6. Frequency distributions of agronomic efficiency for N, P, and K fertilizer for radish. AEN, AEP, and AEK are the agronomic efficiencies of nitrogen, phosphorus, and potassium, respectively (data from radish datasets).

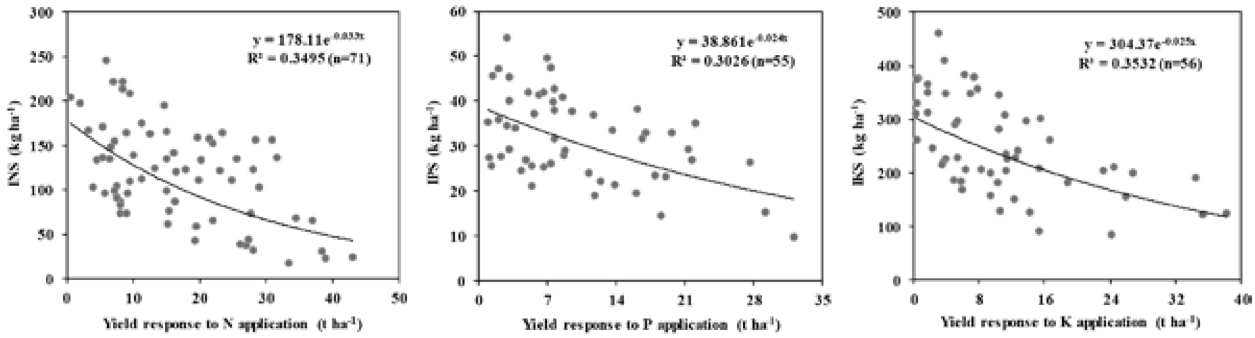

Fig. 7. Relationship between yield response and soil indigenous nutrient supply for radish. INS, IPS, and IKS represent indigenous nitrogen, phosphorus, and potassium supply, respectively (data from radish datasets).

36.4%; and those greater than 200 kg kg^{-1} only accounted for 10.3%. AEP and AEK below 100 kg kg^{-1} accounted for 60.7 and 74.8%, respectively.

Relationship between Yield Response and Indigenous Nutrient Supply

It was detected that the exponential relationships between YR and indigenous soil N, P, and K supply was significantly negative ($P < 0.0001$, Fig. 7), with correlation coefficients (R^2) of 0.35, 0.30, and 0.35, respectively. The indigenous supply of nutrient in soil can be determined by evaluating the YRs in the omission plots, which can be used to identify soil fertility. In addition, in some experimental areas, the absence of fertilizer application did not increase the YR due to high fertility levels in the soils. Thus, YR may act as an indicator of soil fertility for specific regions and fields.

Correlation between Yield Response and Agronomy Efficiency

In the present study, a significant quadratic relationship was observed between YR and AE ($P < 0.0001$, Fig. 8), and the correlation coefficients (R^2) were 0.92, 0.80, and 0.72 for N, P, and K, respectively. The YR can be reflected by the indigenous supply of nutrient in soil; it varies with changes in the indigenous supply of nutrient in soil. The AE is also influenced by fertilizer application, crop management practices, soil indigenous nutrient supply, and regional climatic conditions.

Field Validation of the Nutrient Expert System for Radish

To test the feasibility of the NE system for radish, experiments in 34 farmers' fields were conducted in Tianjin, Shandong, Hebei, Zhejiang, and Beijing during 2016 to 2018. On average, the fleshy root yield of radish under the NE treatment was significantly greater than that under the FP treatment ($P < 0.05$) with an average increase of 2.8 t ha^{-1}, representing an average enhancement of 4.1% (range 0.2–9.3%) across all sites (Fig. 9a). The yield under the NE treatment matched that of the FP treatment in Tianjin, Shandong, and Beijing and exceeded that in Hebei and Zhejiang. Across all the experimental sites, the average net return from the NE treatment was significantly greater than that from the FP treatment. The average net return with the NE treatment was increased relative to that of the FP treatment by 382 to 1214 US$ ha^{-1}, representing an average enhancement of 1000 US$ ha^{-1} (17.9%) ($P < 0.05$) (Fig. 9b). The net return achieved by the increase of yield was 345 US$ ha^{-1}, accounting for 34.5% of the increase in the gross margin.

On average across all the experiments, N use efficiency was significantly greater in the treatment of NE than in the treatment of FP (Fig. 10). Across all sites, the average AEN, REN, and PFPN values in the NE treatment were 76.5 kg kg^{-1}, 31.0%, and 460.7 kg kg^{-1}, respectively, and ranged from 52.8 to 107.8 kg kg^{-1}, 20.6 to 49.4%, and 357.2 to 704.9 kg kg^{-1}. In contrast, the average values of AEN, REN, and PFPN in the FP treatment were 38.4 kg kg^{-1}, 14.4%, and 340.7 kg kg^{-1}, respectively, with ranges from 31.0 to 56.0 kg kg^{-1}, 4.3 to 29.7%, and 229.1 to 859.5 kg kg^{-1}, respectively. The AEN, REN, and PFPN of the NE treatment were significantly improved by 38.1 kg kg^{-1} (99.2%), 15.1% (105.0%), and 120.0 kg kg^{-1} (35.2%), respectively, relative to those of the FP treatment.

DISCUSSION

The indigenous soil nutrient supply is an important indicator of soil fertility (Dobermann et al., 2003). In this study, the average values of INS, IPS, and IKS were 118.7, 28.2, and 208.8 kg ha^{-1}, respectively. The INS in the radish season in China was much greater than that determined by Munkholm and Hansen (2012) in northern Europe (i.e., 65 kg ha^{-1}) and Wahlström et al. (2015) in New Zealand (i.e., 73 kg ha^{-1}). The INS, IPS, and IKS values in our study were also greater than those obtained for grain crops (rice) in China (Xu et al., 2017). Consequently, the effectiveness of fertilization may be strongly weakened by the high indigenous soil nutrient supply. Specially for K, the IKS was remarkably higher than the other indexes, which might be ascribed to historically greater K inputs in radish production (Huang et al., 2017). Similar findings have been presented by Rana et al. (2017) for potato. Consistent with the results of earlier studies reported by Liu et al. (2011) and Cui et al. (2008), overapplication of fertilizers resulted in the accumulation of nutrients in soil, which may be the main reason for the relatively high indigenous soil nutrient supply. Vegetable cropping represents a highly intensive land use in agriculture. The input of agricultural materials such as fertilizers in the production process is usually several times higher than that used for grain crops (George, 2010; Zhang et al., 2017). Thus, the indigenous soil nutrient supply must be carefully considered when making fertilizer recommendations. However, measuring plant nutrient uptake from large numbers of small fields is not feasible. Our study found that there was a significantly negative exponential relationship between YR and indigenous soil nutrient supply (Fig. 7) and negative linear

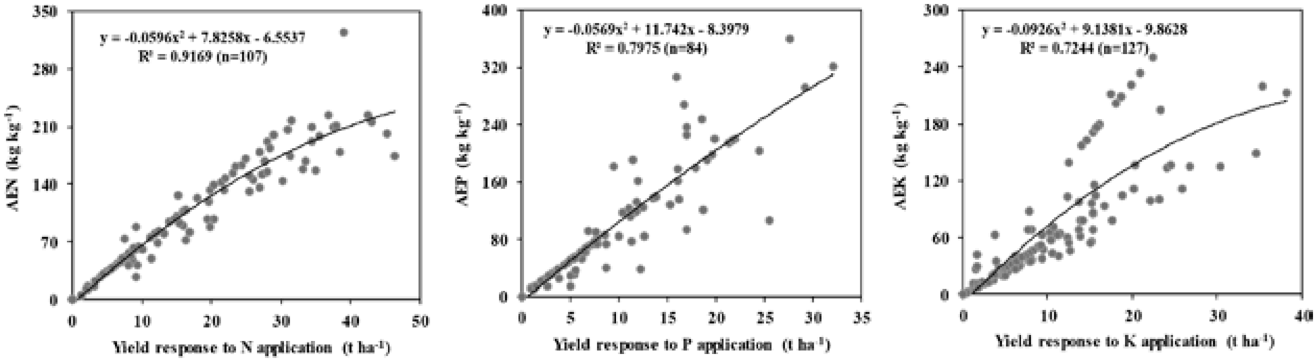

Fig. 8. Relationship between yield response and agronomic efficiency for radish. AEN, AEP, and AEK are the agronomic efficiencies of nitrogen, phosphorus, and potassium, respectively (data from radish datasets).

correlation between YR and relative yield (Fig. 4). Therefore, the indigenous soil nutrient supply can be estimated using the yield from the nutrient omission plots (Dobermann et al., 2003) and relative yield can serve as coefficients to estimate the nutrient-limited yield for a certain *Y*a and soil fertility level when YR data were unavailable (Pampolino et al., 2012). The optimum fertilization rate has also been derived from relative yield or YR vs. indigenous nutrient supply for grain crops in previous studies (Chuan et al., 2013; Xu et al., 2017, 2014).

Inappropriate management practices, including imbalanced fertilizer application ratios, inappropriate application periods, and excessive fertilization, lead to asynchrony between nutrient supply and crop absorption, which results in reduced fertilizer utilization (Agostini et al., 2010). The AE is an important indicator that reflects the fertilizer efficiency, and it is indispensable for fertilizer recommendations. The average AEN in this research (i.e., 104.7 kg kg^{-1}) was comparable to the average value of AEN of 94 kg kg^{-1} investigated by Wu et al. (2016) for vegetable research in China but is only one-half the average value in the United States (i.e., 195 kg kg^{-1}). Therefore, there is still a need for greater efforts toward implementing best management practices to further increase the efficiency of nutrient use for Chinese vegetable production. Different agroecological sites have different agronomic and environmental factors that influence nutrient uptake and *Y*a; thus, the YRs are also different among sites (Reid, 2002). The AE depends on YR and changes with cropping pattern, cropping season, and cropping schemes. Therefore, a dynamic nutrient recommendation method (i.e., NE system) suitable for different cropping conditions is required.

The NE system recommendations ensured that adequate quantity of all nutrients (N, P, K, as well as secondary [Ca, S, and Mg] and micronutrients [B, Zn, and Fe] if deficient) required to achieve the yield target were applied at the critical growth stages of the radish crop (Pampolino et al., 2012). Farmers' fertilizer application rates were always higher than the NE recommendations across most experimental sites in our study (Table 2), but the averaged radish yield and N use efficiency of the FP treatment were significantly lower than that of the NE treatment (Fig. 9a, 9b). In addition, the averaged plant N, P, and K uptake (171, 38, and 237 kg ha^{-1}) in the NE treatment was significantly greater than that in the FP treatment (157, 30, and 218 kg ha^{-1}) (data not shown) across all sites. These findings highlighted the serious problem of excessive or inappropriate fertilizer application in current FP for radish production in China. On the other hand, most farmers apply a large amount of N fertilizer (approximately 50% of the total application rate) before planting, which constitutes a standard management practice to ensure sufficient N supply during the entire growing season. This large amount of basal fertilizer N is prone to loss over a prolonged period since vegetables require time to develop root systems and a significant demand for N (Agostini et al., 2010). The advantages of the NE system with respect to yield and use efficiency of N over the FP treatment arise from the adoption of the 4R nutrient stewardship (Johnston and

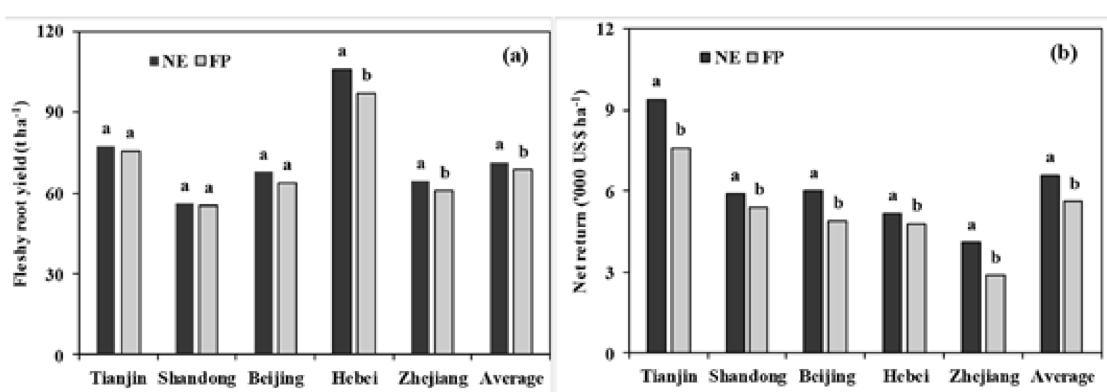

Fig. 9. (a) Fleshy root yield and (b) net return in Tianjin and Shandong (from autumn 2016 to autumn 2018), Hebei and Zhejiang (from autumn 2016 to autumn 2017), and Beijing (from spring 2018 to autumn 2018). Net return represents the gross return above the fertilizer cost. NE and FP were based on the Nutrient Expert for radish decision support system and farmers' practices, respectively. The radish product values and fertilizer prices at the time of the experiment (2016–2018) were \$0.5 to 0.8 kg^{-1} N, \$0.6 to 1.5 kg^{-1} P_2O_5, \$0.6 to 1.1 kg^{-1} K_2O, and \$0.04 to 0.3 kg^{-1} radish; US\$1 = 6.81 RMB. Different lowercase letters above the columns indicate significant differences between treatments at the 0.05 level according to analyses conducted using SAS 9.3 software (data from field validation experiments).

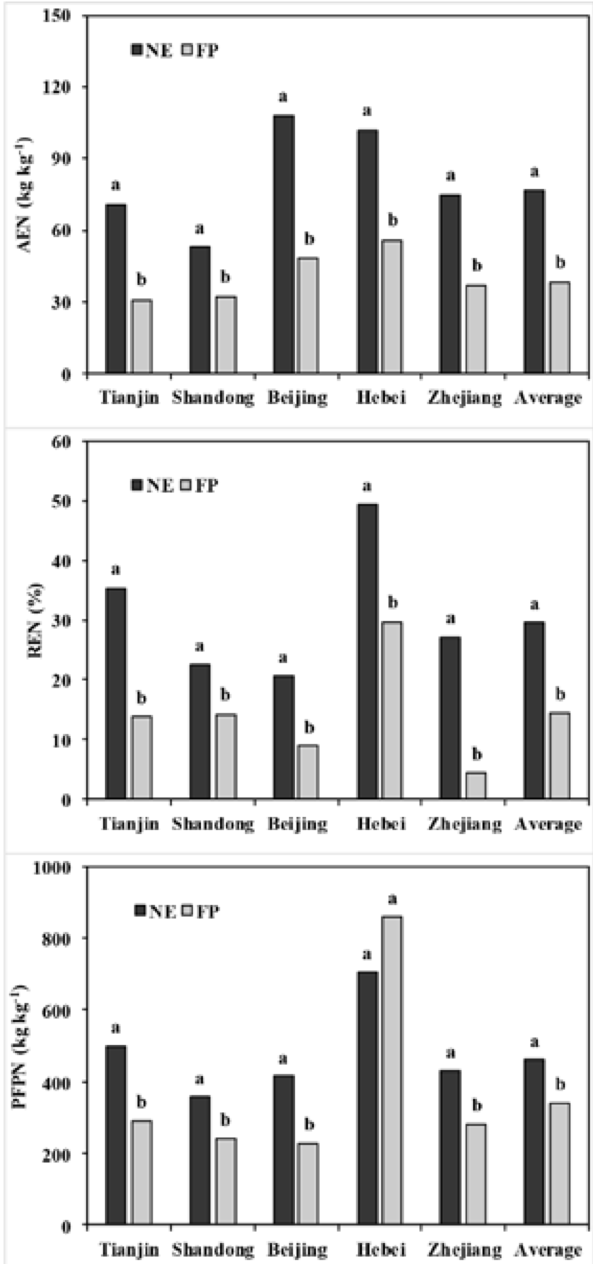

Fig. 10. Comparisons of agronomic efficiency of nitrogen (AEN), recovery efficiency of nitrogen (REN), and partial factor productivity of nitrogen (PFPN) between Nutrient Expert (NE) and farmers' practices (FP) treatments in Tianjin and Shandong (from autumn 2016 to autumn 2018), Hebei and Zhejiang (from autumn 2016 to autumn 2017), Beijing (from spring 2018 to autumn 2018). Different lowercase letters above the columns indicate significant differences between treatments at the 0.05 level according to analyses conducted using SAS 9.3 software (data from field validation experiments).

Bruulsema, 2014). The NE system optimizes the amount of applied fertilizer by reducing N and P rates and adjusting the time and splitting proportion of fertilization, which could have improved the nutrient efficiency of applied fertilizer. However, farmers are not using or are unaware of these practices, which leads to a less-than-optimal yield and nutrient efficiency.

CONCLUSIONS

Datasets regarding radish production and fertilizer application from 2000 to 2017 were built for analyzing the distributions of and relationships among indigenous nutrient supply, YR, relative yield, and AE. The results were used to establish the principles of nutrient recommendations underlying the NE system for radish based on YR and AE. Based on the fertilization management by the NE system, field validation experiments were performed, and the results suggest that the NE system successfully increased radish yield and profits as compared to FP and greatly improved N use efficiency. Therefore, the NE system for radish can be considered as an alternate option for small-holder farmers in radish production who cannot afford or have access to soil testing.

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