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Estimation of NPK requirements for rice production in diverse Chinese environments under optimal fertilization rates

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ABSTRACT

Estimating crop nutrient requirements is essential for informing decisions of optimal nutrient management, but nutrient requirements often vary among climates and soil conditions. We assessed the nitrogen (N), phosphorus (P), and potassium (K) requirements of irrigated rice (*Oryza sativa* L.) in regions throughout China with different climates and soil chemical properties based on 3,896 measurements. We defined nutrient requirements as the aboveground uptake of N, P, and K required to produce 1 Mg of grain. The N and K requirements increased with increasing daily average temperature, solar radiation, N and K fertilizer rate, soil total N, Exchanged-K and organic matter content, total rainfall and potential evapotranspiration (ET) during the rice growing season and decreased with increasing growth duration, and harvest index (HI). In contrast, the P requirement mainly decreased with daily average temperature and solar radiation, increased with P fertilizer rate, soil Olsen-P. The estimated N, P, and K requirements of rice were 15.3, 6.0, and 19.9 kg Mg^{-1} grain in northern China and 21.0, 4.4, and 22.1 kg Mg^{-1} grain in southern China, respectively. The lower N and K requirements in northern China were attributed to lower nutrient concentrations and lower daily average temperature, solar radiation, total rainfall, ET, soil total N, and exchanged-K. The higher P requirement in northern China was mainly attributed to higher grain and straw P concentrations, which could be explained by the lower daily average temperature, solar radiation. Our results update the estimates of rice nutrient requirements based on direct field measurements, and these estimates help address disparities in Chinese nutrient budgets, develop and evaluate models and improve regional nutrient management to support research and policy.

1. Introduction

Determining optimal nutrient management practices requires knowledge of the target yield and crop nutrient requirements, defined as the quantity of aboveground nutrient uptake required to produce 1 Mg of grain (Lory and Scharf, 2003; Zhan et al., 2016). However, nutrient requirements often vary among regions (Ortiz-Monasterio et al., 1997; Xu et al., 2015; Zhang et al., 2017), driven by interactions among nitrogen (N), phosphorus (P), and potassium (K) in different rates and under different climate and soils condition (Witt et al., 1999; Zhang et al., 2012). Crop nutrient requirement studies are typically restricted to a single nutrient applied in site-specific field experiments at research stations (Wu et al., 2013; Zhang et al., 2013; Zhan et al., 2016, 2017), and few have assessed the application of multiple nutrients or compared the effects among widely different agricultural environments.

In China, rice (*Oryza sativa* L.) is cultivated with large climates from warm sub-tropics at 18° N latitude to cool temperate climates at 50° N, covering an area of 31.0 million ha, equivalent to 27.9% of the world's rice output (CASR, 2015; FAO, 2017). There are wide regional variations in the rice growing climate (e.g. temperature and solar radiation), soil conditions, and management practices (Peng et al., 2006; Yang et al., 2015; Xu et al., 2016; Zhang et al., 2017). These wide variations in climate and soil conditions result in large variations in nutrient requirements (Xu et al., 2015). For example, rice N requirements have been reported as 14.8 kg N Mg^{-1} grain in temperate zones (Xu et al., 2015), 17.8 kg N Mg^{-1} grain in subtropical zones (Zhang et al., 2017), and 20 kg N Mg^{-1} grain in tropical zones (Yoshida, 1981). Because of these variations, a systematic, comprehensive, and rigorous assessment of crop nutrient requirements is needed to support nutrient management research and policy development based on regional optimal nutrient inputs.

In this study, we developed a database comprising of 3896 (southern China: $n = 2495$; northern China: $n = 1401$) field measurements of rice production under optimal N, P, and K inputs throughout China and 338 weather stations collecting data covering all experimental sites. The

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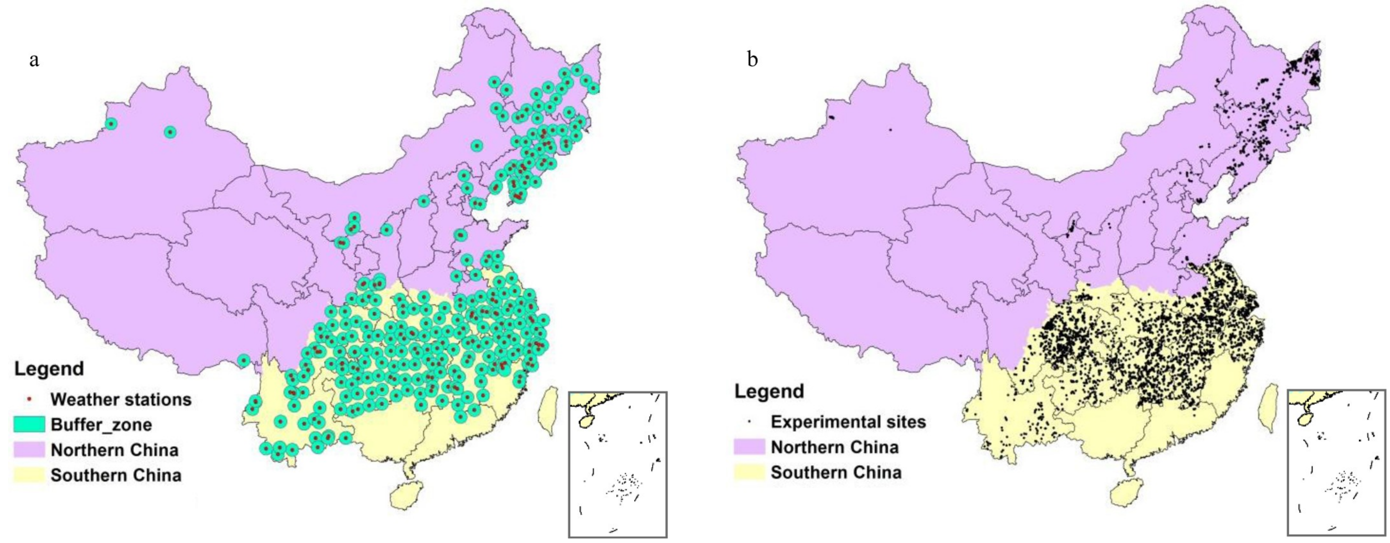

Fig. 1. Distribution of selected weather stations with 3 years of weather data from 2007 to 2010 and the buffer zones with a 50 km radius surrounding a weather station (a) and the experimental sites (b) in the single rice-growing-regions of China.

objectives of this study were to (i) evaluate the relationship between nutrient requirements and climates or soil chemical properties and (ii) determine the N, P, and K requirements in northern and southern China to support optimal regional nutrient management.

2. Materials and methods

2.1. Study area and field experiments

The study region was mainly the single-season irrigation paddy rice-planting cropping system regions in China, which include northern and southern China separated by the Qinling to Huaihe line (Fig. 1). In the north, rice is mainly planted in northeast and northwest China, where the climate is cool and temperate, and crops are grown from early or middle May to middle or late September. In the south, rice is mainly planted along the Yangtze River and in southwestern regions dominated by a subtropical to sub-humid climate, and crops are grown from late May or early June to late September or early October.

A total of 3896 on-farm observations in 422 counties were identified for data collection. The experiments were conducted each year during 2007–2010. All sites were located within a farmer's field and were managed by the farmer. The plot size was about 40 m^2 (5 × 8 m) and received optimal rates of N as urea, P as triple superphosphate, and K as potassium sulphate. In all field experiments, all P fertilizers were applied to the soil prior to transplanting. K fertilizer was applied in two splits of about 60% before transplanting and the remainder at the panicle initiation stage. N fertilizer was applied in three splits of 50% before transplanting, 20% at tillering, and 30% at the panicle initiation stage. In general, farmers ploughed, puddled, and leveled fields before transplanting. The plots were established in a representative area in each field and managed according to the farmer practices, with the exception of fertility treatment levels. No obvious standing water, weeds, diseases, or insect pests were observed at any of the sites during the growing season of rice.

Each site received at least four treatments: 0 (control), optimal nutrient management strategy, below (50% optimal nutrient rate) and above optimal nutrient management (150% optimal nutrient rate). The optimal nutrient management was recommended by experts based on local yield targets and soil tests and other treatment nutrient levels were computed based on the optimum N, P and K rates. The average of all sites and years for the optimal treatments fertilizer rates were 132 ± 36 (mean ± standard deviation) kg N ha^{-1}, 69 ± 11 kg P_2O_5 ha^{-1}, 73 ± 24 kg K_2O ha^{-1}in the northern region and 188 ± 54 kg N ha^{-1}, 66 ± 10 kg P_2O_5 ha^{-1}, 105 ± 35 kg K_2O ha^{-1} in southern China. In this study, only the results for the optimal nutrient rate treatments were discussed. Dry matter, and N, P and K uptake of both grain and straw were analyzed.

2.2. Sampling and laboratory procedures

At maturity, plants were harvested from a 5-m^2 area for each treatment and threshed in the plot, and the grains were dried to determine the grain yield. Ten hills were sampled diagonally from the 5-m^2 harvest area to determine the total aboveground dry weight and harvest index (HI). Mature plant samples were divided into grain and straw. To measure the biomass, all plant samples were oven-dried at 70 °C until reaching a constant weight.

The dried samples were milled and subsequently digested with concentrated H_2SO_4 and H_2O_2. The N concentrations in grain and straw were determined using the Kjeldahl method (Horowitz, 1970). The P concentrations in grain and straw were determined using the molybdate blue colorimetric method (Murphy and Riley, 1962). The K concentrations were determined using a flame spectrophotometer (2655-00; Cole-Parmer, Vernon Hills, IL, USA). In total, 3896 N treatments, 2710 P treatments, and 3357 K treatments were examined for optimal fertilizer management.

Composite soil samples (10 cores per site) were collected from the uppermost 20 cm of the soil profiles at all sites prior to the experiments. The samples were air-dried, pulverized, and passed through 0.25- and 1-mm sieves. Organic matter, total N, Olsen-P, and exchanged-K were analysed using the chromic acid titration method, alkali hydrolysis and diffusion method, $NaHCO_3$ method, and 1.0 mol L^{-1} NH_4OAc extraction method, respectively (Walkley and Black, 1934; Olsen, 1954; Jackson, 1958; Bremner, 1996). The soil pH was determined by pH electrode (water ratio of 1:2.5) (Jackson, 1958).

2.3. Weather data sources, selection and compute

Daily weather data for the period from 2007 to 2010 from a total of 756 stations were obtained from China meteorological Administration (http://data.cma.cn). The selection of a reference weather station for each farm site made following the protocol described in Liu et al. (2017). First, the location of each experimental sites and weather station was entered in a Geographic Information System and overlaid with a map of China. Next, circles with a 50 km radius were drawn around each weather station which represented a zone of impact for each weather station. Finally, we evaluated the location of each experimental site with

Table 1
N, P, K requirements, concentrations of grain and straw, yield, harvest index (HI), growth duration, daily average temperatures, average day/night temperature differences, solar radiations, total rainfall and potential evapotranspiration of rice in growth duration and soil organic matter, total N, Olsen-P, soil exchanged-K for rice in northern and southern China. Means with different letters are significantly different at the 0.05 level.

Parameter	Unit	Total			Northern China			Southern China		
		n	Mean ± SD	Range	*n*	Mean ± SD	Range	*n*	Mean ± SD	Range
N requirement	kg Mg^{-1}	3896	18.5 ± 3.5	11.0–26.2	1401	15.3 ± 3.3b	11.0–19.5	2495	21.0 ± 3.7a	16.4–26.2
Grain N concentration	g kg^{-1}	3896	11.9 ± 2.6	6.4–16.50	1401	9.8 ± 2.8b	6.4–12.8	2495	13.3 ± 2.3a	10.5–16.5
Straw N concentration	g kg^{-1}	3896	6.8 ± 1.9	3.60–10.0	1401	5.5 ± 2.0b	3.60–8.1	2495	7.7 ± 1.7a	5.40–10.0
P requirement	kg Mg^{-1}	2710	5.1 ± 1.5	3.1–8.5	1010	6.0 ± 2.0a	3.5–8.5	1700	4.4 ± 0.8b	3.1–6.1
Grain P concentration	g kg^{-1}	2710	3.2 ± 1.2	2.2–6.9	1010	3.5 ± 1.6a	2.2–6.9	1700	3.0 ± 0.6b	2.2–3.9
Straw P concentration	g kg^{-1}	2710	1.9 ± 1.0	0.9–4.9	1010	2.5 ± 1.3a	1.4–4.9	1700	1.4 ± 0.6b	0.9–2.1
K requirement	kg Mg^{-1}	3357	21.3 ± 5.2	13.0–29.3	1010	19.9 ± 5.3b	13.0–27.3	2237	22.1 ± 5.0a	16.0–29.3
Grain K concentration	g kg^{-1}	3357	3.6 ± 1.5	2.2–6.3	1120	3.8 ± 1.6a	2.2–6.3	2237	3.5 ± 1.2a	2.2–5.3
Straw K concentration	g kg^{-1}	3357	17.5 ± 4.7	9.8–24.8	1120	16.1 ± 4.6b	9.8–22.0	2237	18.6 ± 4.9a	13.0–24.8
Yield	Mg ha^{-1}	3896	8.2 ± 1.6	6.2–10.5	1401	8.7 ± 1.5a	6.8–10.5	2495	8.0 ± 1.4b	6.2–9.8
HI	–	3896	0.50 ± 0.05	0.44 – 0.60	1401	0.52 ± 0.06a	0.44 – 0.60	2495	0.48 ± 0.04b	0.46 – 0.53
Daily average temperature	°C	–	21.6 ± 5.3	15.5–27.8	–	18.5 ± 3.1b	15.5–22.8	–	24.3 ± 2.0a	21.4–27.8
Average day/night temperature difference	°C	–	10.0 ± 1.5	8.1–12.7	–	11.5 ± 0.6a	8.1–10.1	–	8.8 ± 1.1b	9.0–12.7
Daily average solar radiation	MJ m^{-2} d^{-1}	–	15.5 ± 2.4	10.6–23.2	–	14.3 ± 2.7b	10.6–21.1	–	16.4 ± 2.3a	11.3–23.2
Rainfall	mm	–	668 ± 157	126–1384	–	415 ± 153b	126–868	–	714 ± 165a	385–1384
Evapo-transpiration	mm	–	606 ± 192	350–1100	–	564 ± 186b	350–833	–	657 ± 193a	704–1100
Growth duration	day	3896	142 ± 20	90–197	1401	151 ± 21b	99–197	2237	138 ± 19a	90–178
Soil organic matter	g kg^{-1}	3896	28.9 ± 15.4	13.7–52.8	1401	26.6 ± 13.1b	13.7–44.9	2495	31.5 ± 18.2a	3.9–52.8
Total N	g kg^{-1}	3896	1.7 ± 1.0	0.85–2.54	1401	1.4 ± 1.0b	0.85–2.48	2495	1.8 ± 1.0a	0.55–2.54
Soil Olsen-P	mg kg^{-1}	2710	23.5 ± 18.4	10.6–39.9	1010	26.9 ± 15.3a	10.6–44.8	1700	20.1 ± 21.2b	5.4–39.9
Soil exchanged-K	mg kg^{-1}	3357	99 ± 56.2	40.1–178	1120	91.5 ± 50.3b	40.1–155	2237	108 ± 64.4a	69–178
pH	–	1932	6.05 ± 0.98	5.0–7.8	844	6.14 ± 0.44a	5.1–6.6	1088	5.95 ± 0.9b	5.0–7.8

respect to the 50 km buffers drawn around each weather station to select the appropriate weather station for each experimental site. A total of 338 reference weather stations (Fig. 1a) were selected which covered all experimental sites to provide relevant daily weather data (i.e., daily sunshine hours, maximum and minimum temperatures, humidity, and wind speed) during the experimental period.

We used the Angstrom-Prescott equation (Li et al., 2004) to compute the daily solar radiation based on daily sunshine hours. The daily maximum and minimum temperatures were used to calculate the daily average temperature, while temperature, relative humidity, and wind speed were used to calculate the potential evapotranspiration (ET) (Wu et al., 2017). We also computed the daily average of daily averaged temperatures, solar radiation, and the total rainfall and ET for rice growing season for each site over the 3-year period. The average planting dates ranged from May 1 to May 15 for southern rice and from May 15 to May 25 for northern rice. The corresponding average harvesting period of northern rice ranged from September 15 to September 30 and for southern rice, harvesting period ranged from September 25 to October 3.

2.4. Data analysis

We defined nutrient requirements as the aboveground nutrient uptake required to produce 1 Mg of rice grain which were calculated by the following equation:

$$\text{Nutrientrequirement} = (Yg{*}Cg + Ys{*}Cs)/Yg \quad (1)$$

where Yg and Ys represented the yield of grain and straw biomass (kg ha^{-1}) and Cg and Cs represented the nutrient concentration of grain and straw (g kg^{-1}).

To clarify the nutrient requirement response to the climate, soil chemical properties, and plant production parameters, we assumed to be dependent variables (nutrient requirements) and independent variables (climate, and soil chemical properties parameters) within each weather station buffer were used to test the distributions of optimal N requirements of different regions using principal component analysis (PCA) of the vegan package ggbioplot in R (version 3.5.1). Spearman's correlation analysis was also used to assess the influence of climate (daily average temperature and solar radiation, total rainfall and ET of the growing season), soil chemical property (SOM, total N, soil total N, Olsen-P and exchanged-K) and fertilization management on rice N, P, and K uptake requirements.

A specific statistical analysis was carried-out to correct the implicit spurious correlation between N, P, K requirements and corresponding yield (Table 2), this calculation was created by Brett (2004) in the area of Engineering, and used for the first time in agronomy by Ojeda et al. (2018) based on environmental and production variables:

$$r = -CV_X/(CV_Y{}^2 + CV_X{}^2)^{1/2} \quad (2)$$

where CV_X is the CV of aboveground N/P/K total uptake per ha^{-1} and CV_Y is the CV of grain yields. The results of these analyses were presented using the coefficient of determination (R^2) calculated as the square of *r*.

Associations between variables were evaluated using nonlinear correlation analysis. Statistical analyses were carried-out in R (version 3.5.1) through the Rcmdr package (Fox, 2017).

Descriptive statistical analysis was performed to evaluate the average, variability, and standard deviation of each parameter measured. The means were compared using the *t*-test at a 0.05 significance level, using SPSS version 17.0 (SPSS, Inc., Chicago, IL, USA).

3. Results

3.1. Influence of soil chemical properties and climates on N, P, and K requirements

Under optimal fertilizer management, the average rice yield was 8.2 (range of 6.2–10.5) Mg ha^{-1} and the calculated total nutrient uptake averaged 152 (range of 117–186) kg N ha^{-1}, 43 (range of 30–47) kg P ha^{-1}, and 175 (range of 133–210) kg K ha^{-1}, respectively (Table 1). The amount of N, P, and K required to produce 1 Mg of rice grain averaged 18.5, 5.1, and 21.3 kg, respectively. Large variations in nutrient requirements of 11.0–26.2 N Mg^{-1} grain (standard error: 3.5 Mg ha^{-1}, 95% confidence interval), 3.1–8.5 P Mg^{-1} grain (standard error: 1.5 Mg ha^{-1}, 95% confidence interval), and 13.0–29.3 K Mg^{-1} grain (standard error: 5.2 Mg ha^{-1}, 95% confidence interval) were observed in grain yield.

Table 2
Statistical summary of N, P, K requirements (NR, PR, KR) and yield for rice.

No. Obs.	NR vs. yield 3896	PR vs. yield 2710	KR vs. yield 3357
R^2	0.20	0.015	0.19
Regression equation	$y = 42.011 - 11.003x$	$y = 2.247 + 1.194\ln(x)$	$Y = 44.878 - 11.297\ln(x)$
p value	< 0.001	0.082	0.001

With few exceptions, daily temperature and solar radiation were the most influential factors affecting nutrient requirements of rice among all the climate factors. The N and K requirements increased with increasing daily average temperature (N: $r = 0.557$, $p < 0.05$; K: $r = 0.404$, $p < 0.05$) and solar radiation (N: $r = 0.457$, $p < 0.05$; K: $r = 0.334$, $p < 0.05$) during the rice growing season, while the P requirements decreased ($r = -0.374$, $p < 0.05$) with daily average temperature and were negatively correlated with solar radiation (Figs. 2 and 3). The N and K requirements were positively correlated with rainfall (N: $r = 0.268$, $p < 0.05$, K: $r = 0.166$, $p < 0.05$) and ET (N: $r = 0.274$, $p < 0.05$ K: $r = 0.173$, $p < 0.05$) during the growth duration, however, in terms of P, a slight positive correlation trend existed, but it was not significant (Figs. 2 and 3).

The soil chemical properties also affect nutrient requirements. N, P and K requirements were all positively correlated with soil total N, soil Olsen-P and soil exchanged-K, respectively (N: $r = 0.102$, $p < 0.05$; P: $r = 0.136$, $p < 0.05$; K: $r = 0.124$, $p < 0.05$). N and K requirements were also positively correlated with soil organic matters (Figs. 2 and 3, $p < 0.05$). Although all plots received the recommended nutrient applications, the N, P, and K requirements were positively correlated with each fertilizer input (Figs. 2 and 3, $p < 0.05$).

3.2. N, P, and K requirements in northern and southern China

To estimate the regional nutrient requirements, all data were categorised by location as northern or southern China (Wu et al., 2015) based on the Qinling-Huai river line (Fig. 1). Significant differences of N, P, K requirements were observed between northern and southern China (Table 1, Fig. 2). The estimated N requirements were 15.3 (11.0–19.5) kg and 21.0 (16.4–26.2) kg Mg^{-1} grain in northern and southern China, respectively (Table 1). The lower N requirements in northern China were attributed to lower N concentrations in straw and grain and a higher HI. The N concentrations in grain and straw in northern rice were 9.8 (6.4–12.8) g kg^{-1} and 5.5 (3.6–8.1) g kg^{-1}, 34.7% and 32.8% lower than the concentrations in southern rice, respectively. The HI averaged 0.52 (0.43–0.60) and 0.48 (0.46–0.53) in northern and southern China, respectively.

The estimated K requirements were 19.9 (13.0–27.3) and 22.1 (16.0–29.3) kg Mg^{-1} grain in northern and southern China, respectively (Table 1). The lower K requirements in northern China were attributed to lower K concentration in rice straw, but not in grain. The K concentration in straw was 13% lower in northern rice than in southern rice.

The estimated P requirements were 6.0 (3.5–8.5) kg Mg^{-1} and 4.4 (3.1–6.1) kg Mg^{-1} in northern and southern China, respectively (Table 1). The higher P requirements in northern China were attributed to higher P concentrations in straw and grains. The P concentrations of grain and straw in northern China were 3.5 (2.2–6.9) g kg^{-1} and 2.5 (1.4–4.9) g kg^{-1}, which were 16.7% and 79% higher than the corresponding values in southern China.

4. Discussion

We found large variations in rice nutrient requirements among climate, and soil chemical properties in China (Table 1). In northern China, the average daily temperature and solar radiation during the rice growing season were approximately 18.5 °C and 14.3 MJ m^{-2} d^{-1}, which were lower than the respective values in southern China (24.3 °C and 16.4 MJ m^{-2} d^{-1}). The difference between daytime and nighttime temperature in northern China averaged 11.3 °C, 2.7 °C higher than that in southern China (8.8 °C). Overall, the lower daily temperature and solar radiation in northern China suppressed increases in shoot biomass, but likely supported a relatively higher root dry weight, thereby limiting rice N and K accumulation in shoots and root-to-shoot translocation (Clarkson and Warner, 1979; Yan et al., 2012). Additionally, lower temperatures may inhibit the activity of N- and K-regulated enzymes in plants (Atkin and Cummins, 1994) and the kinetics of N- and K-regulated processes (Reich and Oleksyn, 2004).

In this study, the rainfall and ET of northern China were significant lower than the southern China (Table 1). A lower rainfall or a higher potential evapotranspiration might irregularly reduce soil nutrient availability, leading to lower N and K requirements during critical periods. Beyrouty et al. (1994) reported rice subjected to normal flooding consistently responded with the higher nutrient uptake than flush irrigated rice with the lower uptake. Lower nutrient uptake

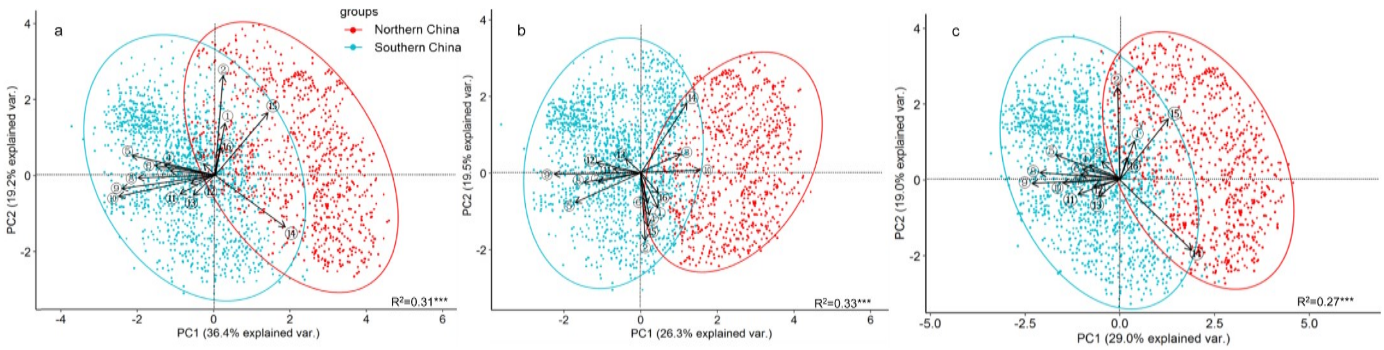

Fig. 2. Principal component analysis (PCA) and correlation analysis of variables and N requirement (a), P requirement (b), K requirement (c).①–⑯ represent growth duration (day), straw biomass (Mg ha^{-1}), Olsen-P, potential evapotranspiration(mm), N fertilizer rate (kg ha^{-1}), rainfall (mm), K fertilizer rate (kg ha^{-1}), solar radiation (MJ m^{-2} d^{-1}), temperature (°C), N requirement/P requirement/K requirement (kg Mg^{-1} grain), soil exchanged- K (mg kg^{-1}), soil organic matter (g kg^{-1}), total N (g kg^{-1}), harvest index (HI), yield (Mg ha^{-1}), P fertilizer rate (kg ha^{-1}), respectively. Temperature and solar radiation are mean daily, and rainfall and potential evapotranspiration are totals in growth duration. Permutational multivariate analysis of variance (PERMANOVA) was used for significance test of the differences between northern and southern China samples using a Euclidean distance. *** indicates significant difference at the 0.001 level.

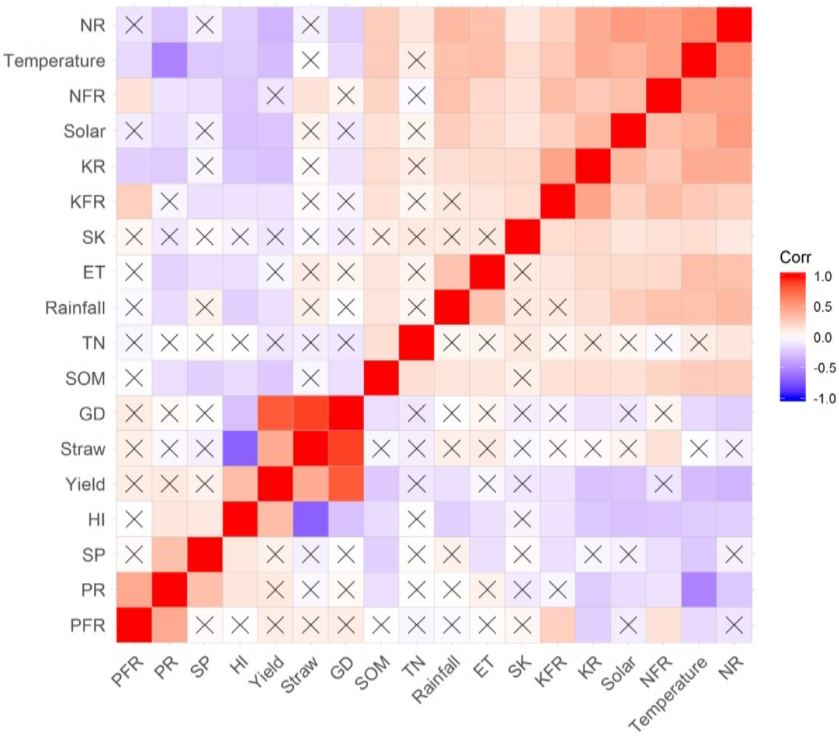

Fig. 3. Spearman correlation coefficient analysis between NPK requirements and its influencing factors. The NR, PR, KR represent the N, P, K requirements. Temperature, solar radiation are mean daily, and rainfall and potential evapotranspiration are totals in growth duration. HI GD represents the harvest index and the growth duration. NFR, PFR, KFR represent the nitrogen (N) fertilizer rate, phosphorus (P_2O_5) fertilizer rate and potassium(K_2O) fertilizer rate. SOM, TN, SP, SK represent the soil organic matter, total N, soil Olsen-P and soil exchanged-K. The correlation coefficient of each two factors is indicated by color. Red color cells represent positive correlations and blue color cells represent negative correlations. "×"cells indicate no significant ($p < 0.05$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

responses are attributed to greater water deficit stress prior to panicle differentiation from lower rainfall (Beyrouty et al., 1994).

With regard to P uptake, decreasing temperatures often force plant tissues to selectively absorb P to offset decreases in the plant metabolic rate (Ahmad et al., 2009). For example, BassiriRad et al. (1996) found that an increase in soil temperature from 5 to 15 °C significantly increased the kinetics of root PO_4^{3-} uptake in *Eriophorum vaginatum*, a tundra species, but a further increase from 15 to 25 °C significantly inhibited the rate of root PO_4^{3-} absorption. Yan et al. (2012) reported that P uptake was inhibited under high P concentrations at higher root-zone temperatures. Gibson and Mullen (2001) found that a larger difference between daytime and nighttime temperatures increased the grain P concentration. Yan et al. (2012) found that increasing the solution temperature from 14 ± 2 °C to 20 ± 2 °C in cucumbers resulted in an increase in N uptake but had no effect on P uptake compared to the unheated control. Adams (1994) found that N and K uptake were closely related to solar radiation, whereas P uptake was more dependent on solar radiation in tomatoes.

Recent literature reported increasing crop nutrient uptake has emphasized the need for greater synchrony between crop nutrient demand and the nutrient supply from all sources throughout the growing season (Chen et al., 2011; Cui et al., 2018). Although N, P, and K fertilization are recommended by local agronomists, low N and K fertilizer application rates may have resulted in lower nutrient requirements. Meanwhile, the organic matter content, total N and soil exchanged K in northern China were significant lower than the southern China, while northern China had significantly higher soil Olsen P readings than southern China (Table 1). Similar results was reported that increasing nutrient supply improves plant growth and root-to-shoot transportation of assimilates, thus promoting plant nutrient uptake (Rufty et al., 1993; Grant et al., 2001). The degree of this inverse relationship varies also depending on genetic. Research has shown that plant variety influences nutrient uptake. For example, Islam et al. (2008) found that indica rice has a greater ability to absorb N and K, whereas japonica rice requires more P. In China, japonica rice is mainly planted in northeast China, and indica rice is generally planted in southern China.

5. Conclusion

Misinterpreting nutrient requirements in different cultivation regions often leads to suboptimal nutrient management practices and prevents farmers from obtaining the maximum attainable yields and profits. In this study, the estimated N, P, and K required to produce 1 Mg of rice grain were 15.3, 6.0, and 19.9 kg in northern China and 21.0, 4.4, and 22.1 kg in southern China, respectively. The differences in the trends in N and K requirements versus P requirements may be explained by the large variations in nutrient concentrations in straw and grain, climates (e.g. temperature, solar radiation, rainfall, ET), and soil chemical properties. However, these factors represent only several of a number of influences that could explain the differences in nutrient requirements; therefore, the potential mechanisms of the effects of environmental conditions on nutrient uptake should be elucidated in future research. The used framework in this study allowed us to explain a vast portion of the spatial variation on nutrient requirement caused by environmental conditions. Our results provided valuable knowledge to feed crop models and improve farm nutrient management decision-making based on model predictions.

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