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RESEARCH ARTICLE

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Optimum nitrogen rate to maintain sustainable potato production and improve nitrogen use efficiency at a regional scale in China. A meta-analysis

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Abstract
The great challenges of ensuring global food security and reducing environmental risk caused by excessive fertilizer inputs require optimizing fertilizer rates to maintain crop production and environmental sustainability. Previous results regarding optimizing N-fertilizer rate for potato were mainly based on case studies and lacked regional-scale information on N-fertilizer management. We hypothesized that regional optimum N rates would increase N use efficiency without sacrificing potato yield compared with low and high N rates. We determined the optimal N-fertilization rates for Chinese potato production at a regional scale based on a dataset of 706 observations from 142 peer-reviewed publications. The linear-plus-plateau model was used to estimate regional optimum N rates, which were 115, 150, 120, and 126 kg N ha^{-1} for the northern, central, southwestern, and southern regions of China, respectively. The target yield could be obtained by applying less N fertilizer when the indigenous N supply was higher across the main potato production region in China. Compared with high N rates, recommended N rates increased N use efficiency and agronomic efficiency by 48.60–81.67% and 17.12–72.90%, respectively, without any yield losses. Recommended N rates also achieved 5.95–14.70% greater yield than low N rates. Here, we show for the first time that, based on a comprehensive literature review, regional optimum N-fertilizer rates result in increased yield and N use efficiency, and reduced negative environmental impacts, all of which play a vital role in maintaining sustainable potato production. The present study highlights the importance of research for achieving a reasonable trade-off between food security and N-fertilizer management for sustainable agriculture.

Keywords Recommended nitrogen rate · Nitrogen use efficiency · Yield · Indigenous nitrogen supply · Environmental sustainability

1 Introduction

The world population is projected to reach 9 billion by the mid-twenty-first century (Godfray et al. 2010). Meeting the future food demand derived from the expansion in the population will require increasing yields without aggravating environmental risks or increasing cropland expansion. Potato (*Solanum tuberosum* L.) production may play an important role in this context since it is the fourth most important food crop in the world after rice, wheat, and maize. China is the largest producer of potato, accounting for around 20% of global acreage and 25% of production (CSB (China Statistical Bureau), 2014). This large production of potato seems to be difficult to achieve if fertilizer, especially nitrogen (N) fertilizer, is not applied (Milroy et al. 2019). In this sense, reasonable N-fertilizer management is an essential agronomic practice to increase crop yields and to reduce environmental risks derived from fertilizer overuse.

However, optimal N application rates for potato production vary greatly among the results of case studies in different regions. As a result, the N application rate required for yield improvement is not easy to predict, and higher amounts of N fertilizer than required by the crop are usually applied. Excessive N application rates may decrease the proportion of tubers in total plant dry matter and result in a reduction in tuber yield (Tadesse et al. 2001) while causing great

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environmental concerns. Nitrogen use efficiency (NUE), defined as the ratio of crop yield to amount of N applied (Moll et al. 1982), can be used to estimate N-fertilizer overuse. High NUE is required to improve sustainability of agricultural systems. However, NUE of global agriculture is estimated to be between 10 and 50% (Mosier et al. 2004), suggesting that excessive N application rates may result in serious problems arising from large N losses and low NUE. Jiao et al. (2013a) reported that the NUE is only 10–32% for potato produced with the local standard N-fertilizer application rate in the Songnen Plain of China. In addition, a recent study from Gansu Province in northwest China showed that N-fertilizer rates beyond a certain range can lead to a reduction in potato yield and losses of excessive N (Yang et al. 2017). In contrast, a previous study indicated that optimized N management could increase NUE and N agronomic efficiency in northeast China (Zhao et al. 2016). Thus, the use of a reasonable N-fertilizer input would be an effective method to maintain crop production and increase NUE (Marcello et al. 2018).

Determination of suitable N-fertilizer application rates has become a major topic in the world due to the overuse of N fertilizer. Although many studies have analyzed the effects of N-fertilizer input on potato production based on field experiments, these results are applicable to specific sites but not to large agro-ecological areas. There has been no specific analysis of the optimal N application rate at a regional scale for the main potato cultivation regions of China. Based on a thorough literature survey, we created a large dataset of N application rate, yield, and NUE for four potato cultivation regions of China (Fig. 1b–e) using a meta-analysis method. The yield and NUE of potato were evaluated to provide a theoretical basis for optimizing N-fertilizer management in the potato cultivation region. Therefore, the specific objective of the present study was to determine, at a regional scale, the optimum N-fertilizer rates that would maintain potato yield and increase NUE. We aimed to answer the following questions: (1) What are the optimum N-fertilizer rates in the main potato cultivation regions of China? (2) Does the indigenous N supply affect N application rate? and (3) What happens to potato yield and NUE if optimum N is applied at a regional scale?

2 Materials and methods

2.1 Study area

Potato is the fourth most important food crop in China and widely distributed due to strong adaptability to the growing environment. However, different potato cultivation areas can be designated to match different climate and production conditions of each region. Considering the biological characteristics, meteorological conditions, and geographic locations, China was divided into four different potato cultivation areas: northern region, central region, southwestern region, and southern region (Fig. 1a) (Teng et al. 1989). The northern region is located in the cold temperate zone and the middle temperate zone, which belongs to the single cropping cultivated region with spring planting and autumn harvest. The cool climate, sufficient sunshine, and high diurnal temperature variation are highly suitable for potato growth and development. The cultivation acreage in the northern region accounts for up to 50% of the total potato acreage in China, and this region is the main potato-producing area in China. The central region is in the warm temperate zone that experiences long summers and high temperatures, and is unfavorable for potato growth. The potato production in the central region accounts for less than 5% of the total production in China. To avoid high temperature stress, potato in the central region is usually planted in spring and autumn. The southwestern region is located in the subtropical and tropical zone. The complex topography and varying altitude in the southwestern region has formed low-altitude river valleys and high-altitude alpine areas. The mixed cropping potato production in the southwestern region is composed of winter planting in the river valleys and spring planting in the high-altitude alpine areas. The Southern region belongs to the subtropical zone with long summers and warm winters. The major food crop produced in the southern region is rice. Potato in the southern region is generally cultivated on the idle land after harvesting rice in winter since most areas are frost-free year round. The meteorological conditions for the four different potato production regions are presented in Table 1.

2.2 Collected data

A search of published papers was performed to collect data on the effects of N fertilizer on potato yield in China. To include as much research as possible, papers published during 2004–2019 in China were found in the China Knowledge Resource Integrated Database (http://www.cnki.net/) and the Web of Science (http://apps.webofknowledge.com/) using search terms including “potato + nitrogen” and “potato + applying fertilizer.” Studies were selected when they met the following criteria: (1) the experiments were carried out in experimental fields, (2) “no N-fertilizer input” was used as a control and various N application rates were used as other treatments, (3) there was at least one pair of control and treatment data, and (4) all other experimental conditions were consistent in a given experiment except for different N treatments. Based on the above criteria, a total of 142 published papers (see References of the meta-analysis) (44 papers for the northern region, 17 papers for the central region, 58 papers for the southwestern region, and 23 papers for the southern region) were selected, among which 140 papers were from the China Knowledge Resource Integrated Database, and 2 papers were from the Web of Science. From these papers, 706 observations (243 from the northern region, 58 from the central

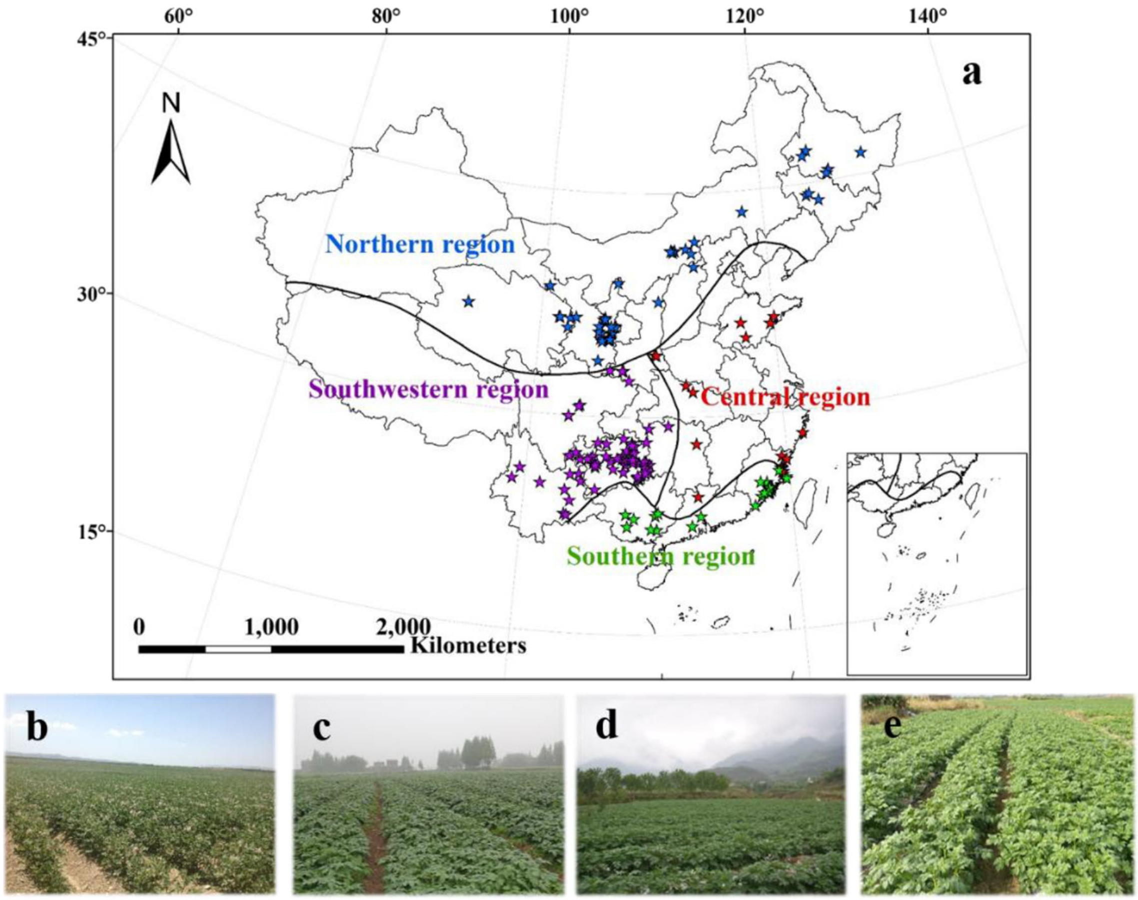

Fig. 1 Location of four potato production regions in China (**a**), and photographs of typical production fields in each region: northern region (**b**); central region (**c**); southwestern region (**d**); southern region (**e**). Stars in panel (**a**) indicate the study sites included in this literature review where primary studies about nitrogen fertilization rates and potato yield have been conducted

region, 266 from the southwestern region, and 139 from the southern region) of yield were used in the analysis of potato yield versus N rate (from zero to various N-fertilizer input). The data obtained in the present study were derived from the experimental sites shown in Fig. 1a.

Chemical fertilizer applications were the focus of the research obtained from the literature search. There were differences in phosphorus and potassium fertilizer inputs between different field experiments, but the phosphorus and potassium fertilizer application rates used between different treatments at a specific site were the same. The phosphorus and potassium rates applied in each given experiment were reasonable based on local production requirements and soil testing, and not limiting potato growth. All field experiments received different levels of urea (46% N), which was viewed as the factor affecting yield variation. In these experiments, potato was planted at the local suitable density at each experimental site. There were differences in climatic conditions and in the physical and chemical properties of the soils at the different field experimental sites. Different potato cultivars suitable for different meteorological conditions were used at the various study locations. Also, irrigation was available for potato growth in around 16% of study sites. Due to rainfed conditions at most research sites, the difference between rainfed and irrigated areas was not considered. These data came from a wide range of cultivars, fertilizer management practices, climatic conditions, soil types, cultivation practices, and others. Sowing date, harvest date of potato, meteorological conditions, and physical and chemical properties of the soil in the experimental fields in the study areas are shown in Table 1.

2.3 Calculation of N fertilizer index

2.3.1 Indigenous N supply

As an indicator of the basic soil fertility, the indigenous N supply (INS) was regarded as the crop yield obtained in plots where N was not applied but other nutrients were applied (Wang et al. 2012). INS played an important role in formulating an N-management strategy. Given that INS reflected the inherent soil N-fertility conditions, INS was considered to be an important factor determining reasonable N rate. Phosphorus and potassium fertilizers were applied at reasonable rates in the field studies reported in the peer-reviewed

Table 1 Summary of sowing date, harvest date, meteorological conditions, and soil properties using collected data from different potato production regions in China

	Northern region	Central region	Southwestern region	Southern region
Sowing date	Late April to mid-May	Early January to mid-March or August	Late December to late January of the next year or late February to mid-March	Mid-November to mid-December
Harvest date	Late August to mid-October	Mid-May to mid-June or November	Mid-May to early June or early July to mid-August	Mid-March to early April
Average annual temperature (°C)	− 2.4 to 8.5	5.8–18.7	10.6–18.1	19.3–24.4
Average annual precipitation (mm)	500–1000	400–1500	680–1300	1100–2800
> 5 °C accumulated temperature (degree days)	2000–3500	3500–6500	4000–7500	6500–9500
Average annual sunshine hours (h)	2179–2960	1653–2780	1139–2078	1540–1929
Frost-free period (days)	105–171	162–286	182–310	305–345
Available N (mg kg^{-1})	94.1–138.2	96.0–119.0	87.4–108.0	62.8–90.0
Available P (mg kg^{-1})	7.6–19.3	9.2–20.8	10.7–20.6	9.5–23.1
Available K (mg kg^{-1})	118.3–158.4	87.0–150.0	121.8–175.1	76.0–157.0
Organic matter (g kg^{-1})	8.9–23.8	7.8–18.8	7.7–18.4	7.2–18.1
pH	6.5–8.1	5.8–7.1	5.6–6.5	5.2–6.0

papers we collected data from, and different N-fertilizer application rates comprised the treatments. Soil N fertility was used to meet the N demand for potato growth when N fertilizer was not applied. Therefore, potato yield obtained without N fertilizer was used as the surrogate for INS (t ha^{-1}).

2.3.2 N use efficiency and agronomic efficiency of N

To assess the use of different levels of N fertilizer, NUE and agronomic efficiency of N (AEN) were introduced in the present study. NUE was defined as the ratio of crop yield to amount of N applied, and indicated agronomic and environmental performance. AEN was defined as the ratio of increase in crop yield between a fertilized plot and a control plot to amount of N applied, and represented the ability of the crop to produce higher yield in response to added N fertilizer. NUE (kg kg^{-1}) and AEN (kg kg^{-1}) were therefore calculated as described by Lassaletta et al. (2014) and Rathke and Behrens (2006) as follows:

$$NUE = Y_N / F_N$$
$$AEN = (Y_N - Y_0) / F_N$$

where Y_N (kg ha^{-1}) is the crop yield in the fertilized plot, Y_0 (kg ha^{-1}) is the crop yield in the control plot, and F_N (kg N ha^{-1}) is the total amount of N applied.

2.4 Data analysis

2.4.1 Statistical evaluation of regression models

To adequately represent the possible shape of the yield–N rate relationship, the response of potato yields to N-fertilizer rate was described using linear, exponential, quadratic, and linear-plus-plateau models. In the regression models, N-fertilizer rate (X) was used in each field experiment as the independent variable, and the corresponding potato yield (Y) was the dependent variable. For the linear model, Y increased linearly with increasing X. For the exponential model, Y increased exponentially with increasing X. For the quadratic model, Y increased with increasing X at relatively low X values, and then decreased with increasing X after reaching a critical X value. For the linear-plus-plateau model, the data points were divided into two sets. In the first set, Y increased linearly with increasing X until Y reached a maximum value at a critical X value. In the second set of data points, additional increases in X beyond the critical X value did not produce any further increase in Y.

Regression analyses produced coefficients of determination (R^2), F values, and P values used to interpret the yield–N rate relationship. In addition, root mean square error (RMSE) values were analyzed in order to assess performance of the regression models calculated from differences between simulated and observed yields.

The linear model was computed as

$$Y = mX + n$$

where m is the coefficient of the linear function and n is the linear intercept.

The exponential model was computed as

$$Y = ue^{vX}$$

where e is a mathematical constant, and u and v are fitting coefficients.

The quadratic model was computed as

$$Y = aX^2 + bX + c$$
$$X_{\max} = -b/(2a), Y_{\max} = \left[-b + \left(b^2 - 4ac\right)^{0.5}\right]/(2a)$$

where a and b are the fitting coefficients of the quadratic function, and c is the quadratic intercept.

The linear-plus-plateau model was computed as

$$\begin{cases} Y = kX + d, \text{if } X < X_{opt} \\ Y = Y_{\max}, \text{if } X \geq X_{opt} \end{cases}$$

where k is the coefficient of the linear function, d is the linear intercept, and X_{opt} is the critical N rate that occurs at the intersection of the linear response and the plateau line that indicates maximum yield (Y_{max}).

The RMSE was computed using the following formula:

$$\text{RMSE }(\%) = \frac{100}{\overline{O}} \times \sqrt{\frac{\sum_{i=1}^{n} (O_i - P_i)^2}{n}}$$

where n is the number of observed and simulated data pairs, O_i and P_i are observed and simulated values, respectively, and $\overline{O}$ is the average observed value. Smaller RMSE values indicate better agreement between simulated and observed values.

Statistical evaluation of the four different regression models in the four potato cultivation regions is shown in Table 2. Higher R^2 and smaller RMSE values were the criteria used for selecting a reasonable regression model. The R^2 values of the quadratic and linear-plus-plateau models were higher than those of the linear and exponential models. In addition, the quadratic and linear-plus-plateau models had smaller RMSE values than the linear and exponential models. The differences in R^2 and RMSE values between the quadratic model and the linear-plus-plateau model were small. Compared with the linear and exponential models, the quadratic and linear-plus-plateau models better described response curves for the yield–N rate relationship, thereby providing reasonable estimates of N-fertilizer input. We compared the results of these two models to identify the optimum N-fertilizer rates (i.e., recommended N-fertilizer rates) required to obtain high NUE and maintain potato yield.

2.4.2 Statistical analysis

The assumptions of normality and homoscedasticity of the residuals were tested using the Shapiro–Wilk test and the Levene test, respectively. The original NUE and AEN data were not normally distributed. Therefore, we performed a logarithmic transform on the NUE data and a square root transform on the AEN data. One-way ANOVA was used to compare the INS between different regions using SPSS 22.0 (https://www.ibm.com/products/spss-statistics). When the ANOVA was significant, means were compared by least significant difference (LSD) calculated at $p < 0.05$. An exponential equation was used to simulate NUE and AEN responses to N-fertilizer rate using SPSS 22.0. To establish the best curve defining the response of yield to N-fertilizer rate, different regression models were applied. The linear, exponential, and quadratic relationships between yield and N rate were quantified using SPSS 22.0, and the linear-plus-plateau equation for the yield-N rate relationship was determined with the SAS System 9.2 (https://www.sas.com/). Figures and tables were made using Microsoft Excel software (https://www.microsoft.com/en-us/). The map figure was created with ArcGis 10.2 software (https://www.esri.com/).

3 Results and discussion

3.1 Comparison of models and determination of optimum N rate

The effect of different N-fertilizer application rates on potato yield was analyzed in the four producing regions of China using a quadratic model and a liner-plus-plateau model (Fig. 2). The northern region showed the greatest mean yield followed by the central, southern, and southwestern regions, respectively. When using the quadratic model, maximum yields were obtained when critical N-fertilizer rates were 178, 251, 217, and 218 kg N ha^{-1} in the northern, central, southwestern, and south regions, respectively, whereas the linear-plus-plateau model estimated critical N-fertilizer rates of 115, 150, 120, and 126 kg N ha^{-1} for maximum yields in the northern, central, southwestern, and south regions, respectively. The maximum yield estimated by the quadratic model was 4.33–7.06% greater than that predicted by the linear-plus-plateau model in the four regions. However, N application rates to obtain these maximum estimated yields based on the quadratic model were 54.78, 67.33, 80.83, and 73.02% higher than those calculated by the linear-plus-plateau model for the northern, central, southwestern, and south regions, respectively. Given these results, we could conclude that use of the linear-plus-plateau model to estimate the optimum N rate could prevent N-fertilizer overuse without losing a significant amount of yield. Consequently, we used this model to estimate recommended N-fertilizer rates, which were 115, 150, 120, and 126 kg N ha^{-1} for the northern, central, southwestern, and southern regions, respectively.

Compared with the quadratic model, the linear-plus-plateau model produced lower optimum N rates without significant yield losses. By comparing the results of the quadratic and linear-plus-plateau models, Liu et al. (2016) selected the linear-plus-plateau model to determine optimal N rate. Li et al. (2019) also reported that the linear-plus-plateau model was used to identify recommended N input. In addition, the optimum N rates estimated by the linear-plus-plateau model in our study were similar to the

Table 2 Statistical evaluation of the different regression models

Regions	Statistics	Linear model	Exponential model	Quadratic model	Linear-plus-plateau model
Northern region	RMSE	24.55%	25.02%	22.05%	22.67%
	R^2	0.1523	0.1557	0.3162	0.2775
	F value	43.29	44.45	55.49	46.09
	P value	< 0.001	< 0.001	< 0.001	< 0.001
Central region	RMSE	27.66%	28.55%	26.13%	25.62%
	R^2	0.2668	0.2773	0.3637	0.3710
	F value	20.38	21.49	15.72	16.22
	P value	< 0.001	< 0.001	< 0.001	< 0.001
Southwestern region	RMSE	25.53%	26.09%	24.39%	24.07%
	R^2	0.1772	0.1980	0.2736	0.2688
	F value	56.86	65.20	49.54	48.35
	P value	< 0.001	< 0.001	< 0.001	< 0.001
Southern region	RMSE	25.92%	26.60%	23.81%	24.10%
	R^2	0.1783	0.2077	0.3093	0.2892
	F value	29.73	35.91	30.45	27.66
	P value	< 0.001	< 0.001	< 0.001	< 0.001

RMSE root mean square error, R^2 coefficient of determination, *P value* significance of the regression

results reported by Liu et al. (2010a). Therefore, the linear-plus-plateau model should be considered a feasible option to estimate reasonable N-fertilizer application rates.

3.2 Indigenous N supply in four production regions

We calculated INS to test its influence on the optimum N-fertilizer rate for each region. The national mean INS was 18.98 t ha^{-1}, ranging from 5.90 to 30.77 t ha^{-1} (Fig. 3a). The mean INS values were 20.95, 18.08, 17.70, and 17.90 t ha^{-1} in the northern, central, southwestern, and south regions, respectively (Fig. 3b). We predicted that lower N input would be needed to obtain target yield under higher INS conditions. The mean INS of the Northern region was significantly higher than that in the other regions (Fig. 3b). Correspondingly, this region had the lowest optimum N rate and highest estimated yield (Fig. 2). This fact suggests that INS plays an important role in the determination of optimum N-fertilizer rate and final yield. It appears that when INS is high, less N fertilization is needed to produce a certain yield. A similar conclusion was reached by Jing et al. (2007) regarding the role of INS for two rice cultivars. They showed that a higher INS was related to a lower N application rate. Therefore, INS might be an important factor affecting the determination of optimum N-fertilizer rate.

3.3 N use efficiency and agronomic efficiency of N under different N input

To establish response curves of NUE and AEN to N-fertilizer rate, the trends in NUE and AEN under different N inputs were analyzed (Fig. 4). Both NUE and AEN decreased with increasing N rates, with average values of 207.38, 170.70, 187.87, and 152.89 kg kg^{-1} for NUE, and 51.83, 45.02, 47.35, and 42.84 kg kg^{-1} for AEN in the northern, central, southwestern, and south regions, respectively. van Bueren and Struik (2017) reported that NUE was relatively high at low N levels and decreased with increasing N-fertilizer rates. High NUE was probably due to high green leaf area index and leaf N concentration, resulting in greater accumulated dry matter and greater N uptake from the soil (Qiang et al. 2019). In addition, well-managed systems can result in high AEN at low N-fertilizer rates (Dobermann 2007). Synchronizing fertilizer-N supply with crop N demand through reasonable N-fertilizer management will improve both NUE and AEN.

3.4 Yield and N use efficiency of the recommended N rate

N-fertilizer inputs above and below the recommended N rate for each region were viewed as high N rates and low N rates, respectively. The N-fertilizer rate applied in 77, 69, 68, and 67% of various N treatments at all sites exceeded the recommended N input, and the remaining 23, 31, 32, and 33% of the cases received N-fertilizer rates that were lower than the recommended N rate in the northern, central, southwestern, and south regions, respectively. To compare differences in yield, NUE, and AEN between low, recommended, and high N rates, the corresponding yields at low and high N rates were calculated based on the linear-plus-plateau model. The NUE

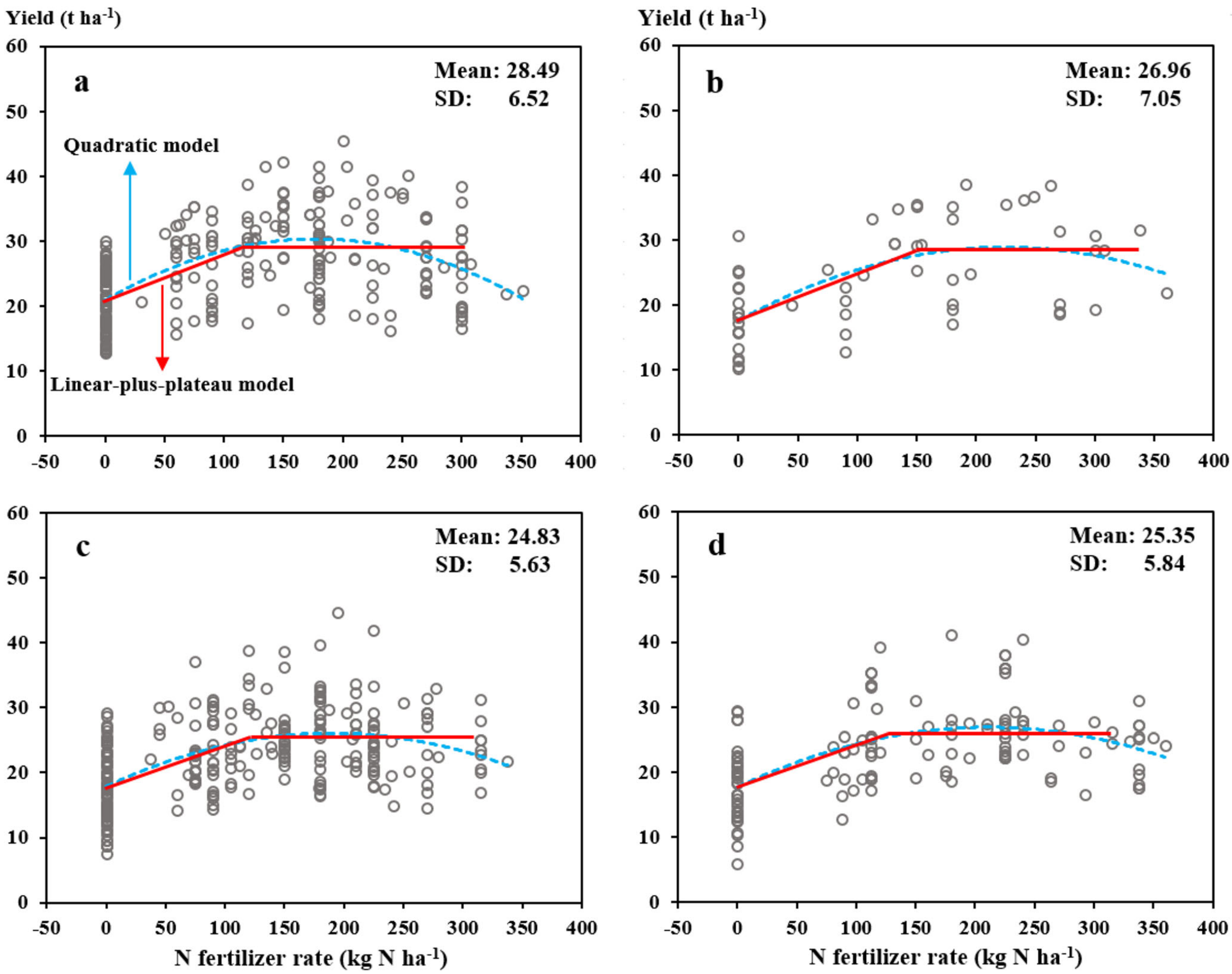

Fig. 2 Yield as a function of N fertilizer rate in four potato production regions in China. **a** Northern region; **b** central region; **c** southwestern region; **d** southern region. Mean, the average value of potato yield in the fertilized plot; SD, standard deviation. Quadratic model: $y = -0.0003x^2 + 0.1066x + 20.902$ (northern region); $y = -0.0002x^2 + 0.1005x + 17.637$ (central region); $y = -0.0002x^2 + 0.0869x + 17.842$ (southwestern region); $y = -0.0002x^2 + 0.0873x + 17.670$ (southern region). Linear-plus-plateau model: $y = 0.0701x + 21.0488x < 115$, $y = 29.11x \geq 115$ (northern region); $y = 0.0708x + 17.6635x < 150$, $y = 28.27x \geq 150$ (central region); $y = 0.0634x + 17.8733x < 120$, $y = 25.48x \geq 120$ (southwestern region); $y = 0.0650x + 17.7001x < 126$, $y = 25.91x \geq 126$ (southern region)

(or AEN) values at low, recommended, and high N rates were also calculated using the exponential relationships between the N rate and NUE (or AEN).

Compared with the yield of the low N rate, the recommended N rate increased yield by 10.77, 14.70, 10.13, and 5.95% in the northern, central, southwestern, and south regions, respectively (Fig. 5). Van Dingenen et al. (2019) reported that limited N availability produced lower potato yield than optimal N availability due to a reduced number of tubers. Low N input might deplete the soil N pool resulting in not enough N to meet the demand for crop growth and ultimately reduced yield (Vrignon-Brenas et al. 2019). Although yields at the recommended N rate were comparable with yields at high N rate in all regions, the recommended N rate increased NUE by 64.82, 48.60, 54.97, and 81.67%, and improved AEN by 72.90, 17.12, 39.14, and 60.93% for the northern, central, southwestern, and south regions, respectively (Fig. 5), revealing that high N-fertilizer application rates led to a waste of the N resource. Shillito et al. (2009) analyzed the spatial response of potato yield to N rate and indicated that additional N input above the recommended N rate would result in excessive N loss from the soil. A reasonable N rate should be used to ensure high yield and NUE. A low N rate would limit potential yield increase, while a high N rate would lead to N surplus and aggravate environmental risk. In the present study, the recommended N rate achieved the two goals of maintaining potato yield and improving NUE. Use of the recommended N rate to maintain potato yield while improving NUE could be formulated as a general management proposal at a regional scale.

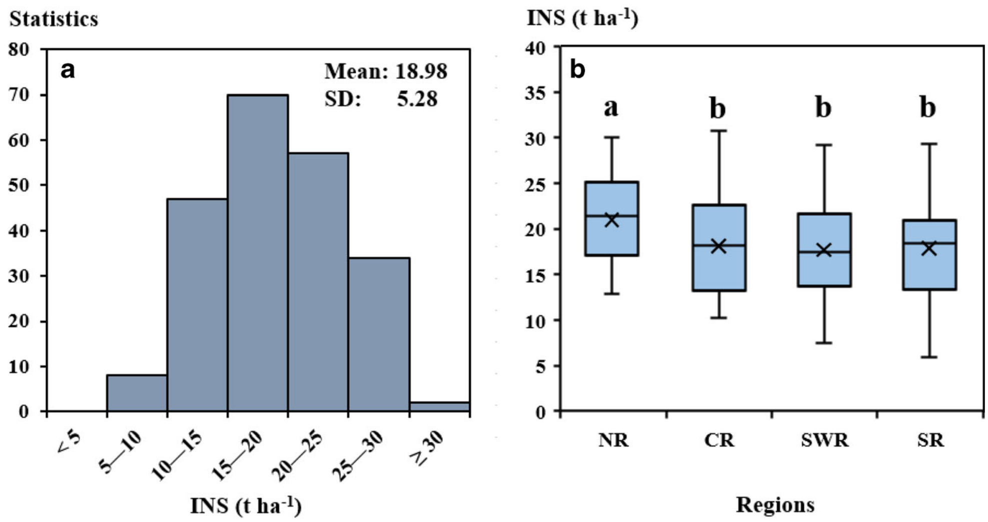

Fig. 3 Frequency distribution of indigenous N supply (INS) from all study regions across China (**a**) and comparison of INS between different potato production regions in China (**b**). Mean, the average value of INS across all regions; SD, standard deviation. NR, northern region; CR, central region; SWR, southwestern region; SR, southern region. Cross and solid lines indicate mean and median value, respectively. The box boundaries indicate the upper and lower quartiles, and the whisker caps indicate the 90th and 10th percentiles. Different lower case letters in panel (**b**) indicate significant differences in mean INS between regions at $P < 0.05$. Mean INS values between regions are compared according to one-way ANOVA: $F = 6.46$, $P < 0.001$, $LSD_{(NR\text{-}CR)} = 2.56$, $LSD_{(NR\text{-}SWR)} = 1.59$, $LSD_{(NR\text{-}SR)} = 1.94$, $LSD_{(CR\text{-}SWR)} = 2.57$, $LSD_{(CR\text{-}SR)} = 2.80$, $LSD_{(SWR\text{-}SR)} = 1.95$

3.5 Uncertainty of optimum N rate for different research targets and specific sites

When optimizing N-fertilizer management, different research targets can result in different optimum N rates. Ying et al. (2017) reported that the optimum N rates needed to maximize values of yield, private profitability, ecological benefits, and social benefits were not the same. Economic income and environmental costs are sometimes considered when determining reasonable N application rates. Because these indicators were calculated by yield directly or indirectly, maximizing crop yield was generally regarded as the number one goal when evaluating a reasonable N application rate (Vos 2009). In the present study, the optimum N rate would definitely be different from that identified by the yield if the research target was to pursue economic income, ecological benefit, or other goals.

Reference N application rates can be determined from a literature survey in order to improve N-fertilizer management for a large-scale region. However, reasonable N inputs identified based on results obtained from studies conducted at a specific site might not be applicable across a large region. Results obtained from several sites across a region could provide relatively reliable guidance for regional N management (Zhang et al. 2018). In our study, estimated N rates were obtained from various field experiments that considered the effects of graded applications of N fertilizer, and not from farmers' typical N-fertilizer application rates, which basically represented the reference N levels at a regional scale. Due to differences in soil and climate conditions between various sites, the N input appropriate for a specific site should be adjusted to match local conditions (Morteza et al. 2018). In addition to uncontrollable factors (such as climate), N-fertilizer input should consider potato varieties and management practices used. Modern potato varieties usually have higher recommended N-fertilizer application rates than heritage varieties (Fandika et al. 2016). Using optimized management practices could reduce the N-fertilizer application rate needed to achieve the target yield. Regulating site-specific N application rates is essential when considering different varieties and management practices. However, unreasonable N-fertilizer applications are usually applied in most of the regions, and these rates are based on experience rather than on crop growth requirements for N (Peng et al. 2010). The overuse of N fertilizer generally does not lead to a significant increase in yield at sites with suitable production conditions and advanced management practices, but can cause great environmental problems. Sites with high N input should be required to reduce N application rate as much as possible. The negative impact of insufficient N input on yield should also not be ignored. To avoid yield loss, sites with low INS or unsuitable climate conditions should reasonably increase N input.

4 Conclusions

The relationship between potato yield and N-fertilizer application rate was estimated to determine the optimum N rate at a regional scale, which were 115, 150, 120, and 126 kg N ha^{-1} for the northern, central, southwestern, and southern regions of China, respectively. We found that N use efficiency and

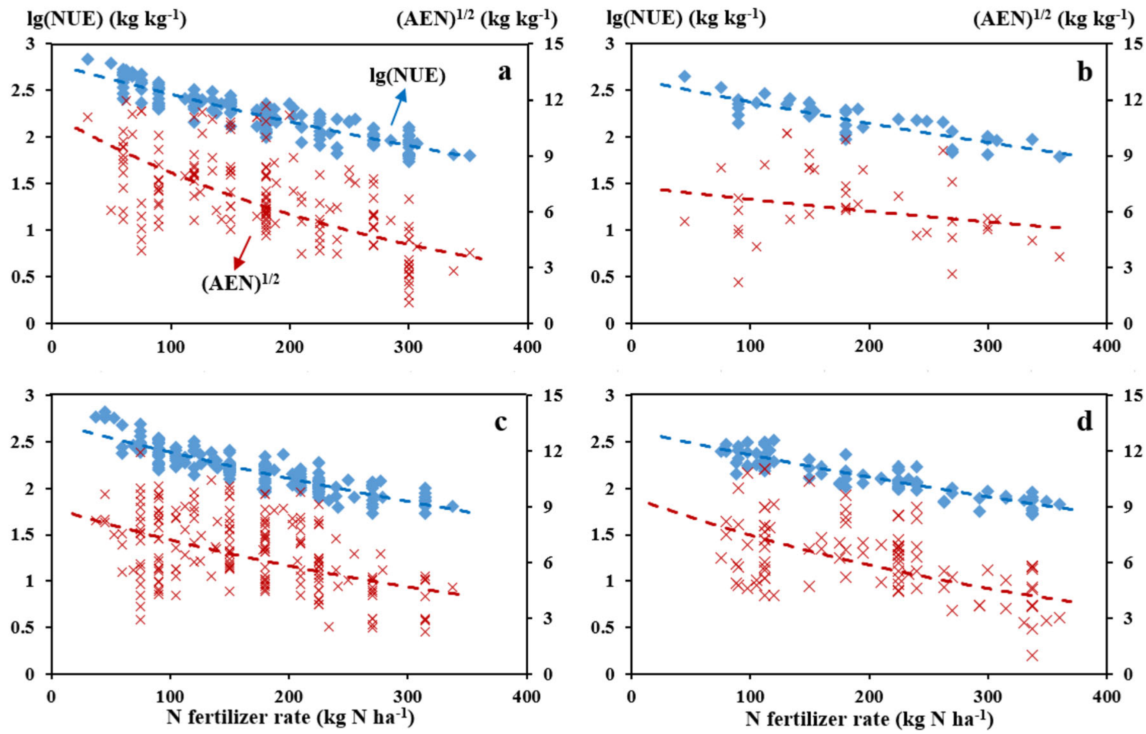

Fig. 4 The N use efficiency (NUE) and agronomic efficiency of N (AEN) at different N fertilizer rates in four potato production regions in China. **a** Northern region; **b** central region; **c** southwestern region; **d** southern region. Regression equations for lg (NUE): $y = 2.79e^{-0.001x}$ $R^2 = 0.8190$*** $F = 723.87$ (northern region); $y = 2.63e^{-0.001x}$ $R^2 = 0.7086$*** $F = 89.97$ (central region); $y = 2.71e^{-0.001x}$ $R^2 = 0.7939$*** $F = 716.43$ (southwestern region); $y = 2.62e^{-0.001x}$ $R^2 = 0.8061$*** $F = 403.19$ (southern region). Regression equations for $(AEN)^{1/2}$: $y = 11.21e^{-0.003x}$ $R^2 = 0.3930$*** $F = 103.59$ (northern region); $y = 7.36e^{-0.001x}$ $R^2 = 0.0580$ $F = 2.28$ (central region); $y = 8.96e^{-0.002x}$ $R^2 = 0.2260$*** $F = 54.32$ (southwestern region); $y = 9.53e^{-0.002x}$ $R^2 = 0.3042$*** $F = 42.41$ (Southern region). *** indicates significance at the 0.001 level

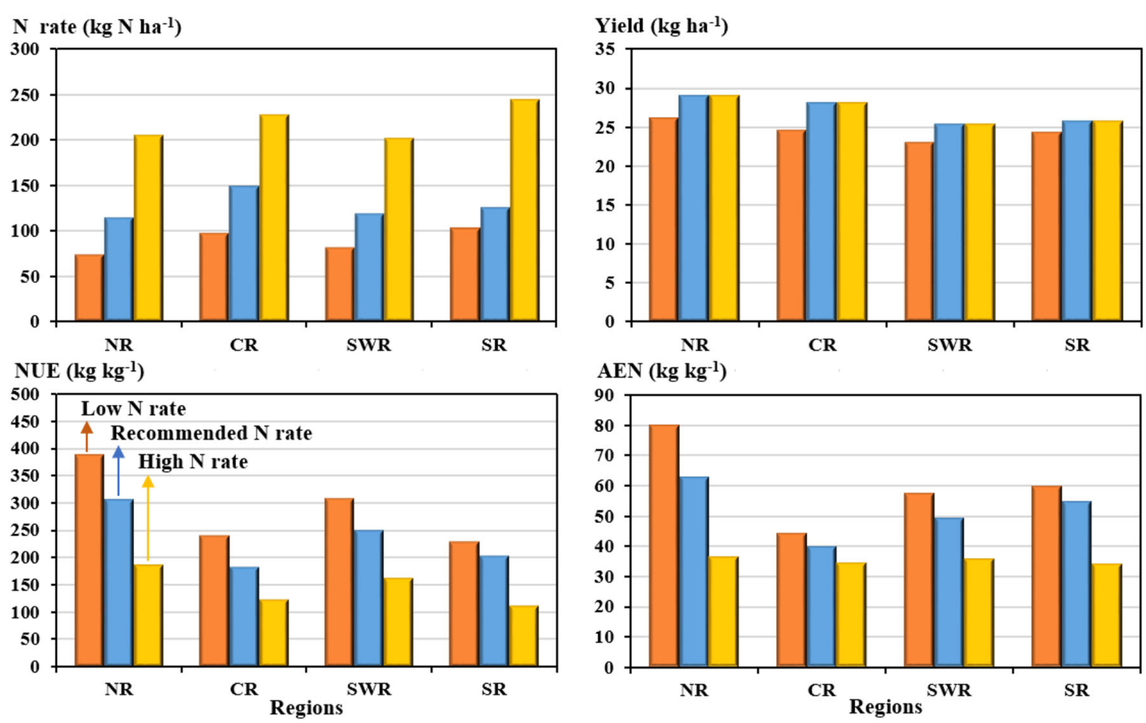

Fig. 5 The yield, N use efficiency (NUE), and agronomic efficiency of N (AEN) under three N rate levels in the northern (NR), central (CR), southwestern (SWR), and southern (SR) potato production regions of China

agronomic efficiency could be improved without potato yield losses based on the estimated N rate. N-fertilizer application rates below the recommended N rate resulted in yield losses of 5.95–14.70%. Yields obtained under the recommended N rate were equivalent to yields at high N rates. However, using the recommended N rate increased N use efficiency by 48.60–81.67% and agronomic efficiency of N by 17.12–72.90%. As a result, potato yields may not be significantly increased when excessively high N-fertilization rates are used, and moderate reductions in N-fertilizer input should be considered. N-fertilizer rate should be increased in areas with poor soil fertility or unsuitable climate conditions in order to reduce potato yield losses. This evaluation of regional N-fertilizer application rates may be a useful reference providing a theoretical basis for how to maintain crop production while optimizing N-fertilizer management. These results are of great significance for recommending production practices resulting in sustainable development of agricultural systems.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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