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Spatial Variability Analysis of Wheat Nitrogen Yield Response: A Case Study of Henan Province, China

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Abstract: The overapplication of nitrogen to wheat reduces profits and has adverse environmental consequences. Machine learning techniques are employed to identify the factors that hold the most potential in improving nitrogen recommendations. The database used in our analysis consisted of a formula fertilization project, the second soil census of China, and cultivated land fertility evaluation. The results showed that the wheat nitrogen yield response was mainly concentrated around 1300–2400 kg/ha in Henan Province, with the highest values observed in the southern and eastern regions and the lowest in the northern region. The soil nitrogen content, nitrogen fertilizer, wet nitrogen deposition, dry nitrogen deposition, and soil nitrogen supply capacity were mainly concentrated around 0.65–1.30 g/kg, 173–203 kg N/ha, 15–39 kg N/(ha yr), 7–49 kg N/(ha yr), and 105–150 kg N/ha, respectively. When comparing the spatial distribution of the soil nitrogen content, nitrogen fertilizer, and nitrogen deposition, we found that the soil nitrogen supply capacity emerged as the predominant factor controlling wheat grain production. Soil types, precipitation, and temperature demonstrated a notable positive correlation with the soil nitrogen supply capacity. Given this background, it would be unreasonable to rely solely on the soil nitrogen content as the standard for fertilizer management. Particularly in high-yield fields, our focus should be on preserving optimal soil fertility by placing greater emphasis on the soil nitrogen supply capacity rather than simply reducing fertilizer application during wheat growth.

Keywords: wheat nitrogen yield; spatial variability; soil nitrogen; nitrogen fertilization; soil nitrogen supply capacity

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1. Introduction

Nitrogen fertilizer is vital in fulfilling the increasing food demand by supporting crop production [1]. However, excessive nitrogen fertilizer application can lead to various environmental issues, such as soil acidification, greenhouse gas emissions, and water eutrophication [2]. It is essential to apply nitrogen fertilizer rationally to ensure sustainable agriculture. Therefore, numerous nitrogen management practices have been developed to optimize nitrogen fertilization and enhance management techniques [3,4]. Several studies have shown that the nitrogen use efficiency in crop production can be improved by combining nitrogen fertilization application management to maximize yield [5–7]. Saudy et al. (2020) showed that nitrogen use rationalization significantly enhanced wheat yield and its components for production by a 2-year field experiment [8].

In wheat production, nitrogen is primarily derived from both fertilizer and soil sources [2,9]. According to Ju et al. (2002), approximately 45% of wheat nitrogen uptake came from nitrogen fertilizer, while the other 55% was from soil nitrogen mineralization during the mature period [10]. However, soil nitrogen mineralization is also affected by the quantity of nitrogen fertilizer applied throughout wheat growth. Lower nitrogen application promotes soil mineralization and nitrogen use efficiency for crop growth [10,11], which is directly related to the soil nitrogen supply capacity. The soil nitrogen supply capacity refers to the inherent ability of the soil to provide a sustainable supply of nitrogen to crops, which can be expressed by the crop's nitrogen uptake without nitrogen fertilization. The soil nitrogen content does not reflect the soil nitrogen supply capacity, as it is only a relative value obtained through chemical methods [12,13]. Therefore, both the soil nitrogen and nitrogen supply capacity are essential for fertilization management.

Additionally, several studies have demonstrated that atmospheric deposition (dry and wet) contributes 80–90 kg N/ha per year in North-Central China, which also influences wheat production [14–16]. Li et al. (2020) showed soil biological nitrogen fixation of about 63 kg N/ha per year in Henan Province [17], but the value was less than nitrogen deposition. We can also think of biological nitrogen fixation as a part of soil nitrogen supply capacity, when the value is equal to the actual nitrogen by wheat uptake. Thus, we used nitrogen fertilizer, soil nitrogen content, soil nitrogen supply capacity, and nitrogen deposition to determine the main factor affecting wheat production.

Henan Province is a key wheat-producing area in China and plays a significant role in ensuring national food security. The amount of fertilizer applied reached 935 kg/ha in 2011, far exceeding the internationally recognized safe limit of 225 kg/ha, and nitrogen use efficiency is as low as 30% in some areas. Saudy et al. (2020) showed that reducing applied nitrogen fertilizer by 25% could enhance nitrogen use efficiency to about 60% [8], so it is crucial to implement nitrogen fertilizer reduction and efficiency enhancement technologies in Henan Province. While various fertilizer efficiency experiments have been carried out by agricultural technology departments following the implementation of the soil formula fertilization project, experimental data have mainly focused on classical regression analysis [18,19]. Spatial analysis refers to the evaluation of nitrogen productivity during wheat growth at a regional scale. It involves studying how the wheat yield is influenced by the soil nitrogen content, nitrogen fertilizer application, nitrogen deposition, and soil nitrogen supply capacity. This analysis provides insights into the spatial patterns of nitrogen productivity's influence on wheat yields, allowing for a better understanding of the factors that affect wheat yields. The aim of this investigation is to reduce the application of nitrogen fertilization to save input costs and enhance the nitrogen use efficiency without negatively affecting grain yields, as well as reduce adverse environmental impacts.

2. Materials and Methods

2.1. Study Areas and Soil Types

Henan Province is located in the central region of China, along the middle and lower reaches of the Yellow River. The north-to-south span is 31°23′–36°22′, and the east-to-west span is 110°21′–116°39′ (Figure 1). Henan Province governs 17 prefecture-level cities, with a land area of 167,000 km^2, accounting for 1.72% of the land area of the country. The soil types in Henan Province are diverse and affected by climate, parent material, hydrology, and human activities. The dominant soil types are fluvo-aquic soil, cinnamon soil, red clay, yellow cinnamon soil, yellow-brown soil, lime concretion black soil, and paddy soil. According to World Reference Base for Soil Resources (WRB) classification, they are categorized as Cambisols, Luvisols, and Anthrosols. The most widely distributed is fluvo-aquic soil (Cambisols), which accounts for 32% of Henan Province, and fluvo-aquic soil is mainly distributed in the eastern region of Henan Province. Wheat is the main food crop, and the main wheat cultivars are Bainong aikang (58), Yumai (70), and Zhengmai (366).

2.2. Data Collation and Analysis

A total of 729 soil samples were collected for wheat nitrogen yield response testing (Figure 2a). There were 358, 117, 18, 83, 20, 92, and 41 soil samples categorized as fluvo-aquic soil, cinnamon soil, red clay, yellow cinnamon soil, yellow-brown soil, lime concretion black soil, and paddy soil, respectively. We also collected 3370, 271,645, and 2277 soil samples to determine nitrogen content in 1980, nitrogen content in 2010, and recommended fertilization for wheat in 2010, which explained the spatial variability in wheat nitrogen yield response (Figure 2b–d). The data came from field experiments in the formula fertilization project in 2010, the second soil census in 1980, soil testing and formula fertilization and cultivated land fertility evaluation database in 2010, and the "three-zone demonstration" experiment of Henan Province, respectively (Table 1). These data points covered a wide range, including cities, counties, and districts of Henan Province. The original data on soil nitrogen in 1980 had no specific coordinates. We used ArcGIS 10.7 based on the sampling text records and combined the 1:50,000 soil map with the 1:10,000 administrative division map for location calibration. We constructed a soil sample database to ensure the accuracy of position and scientific basis.

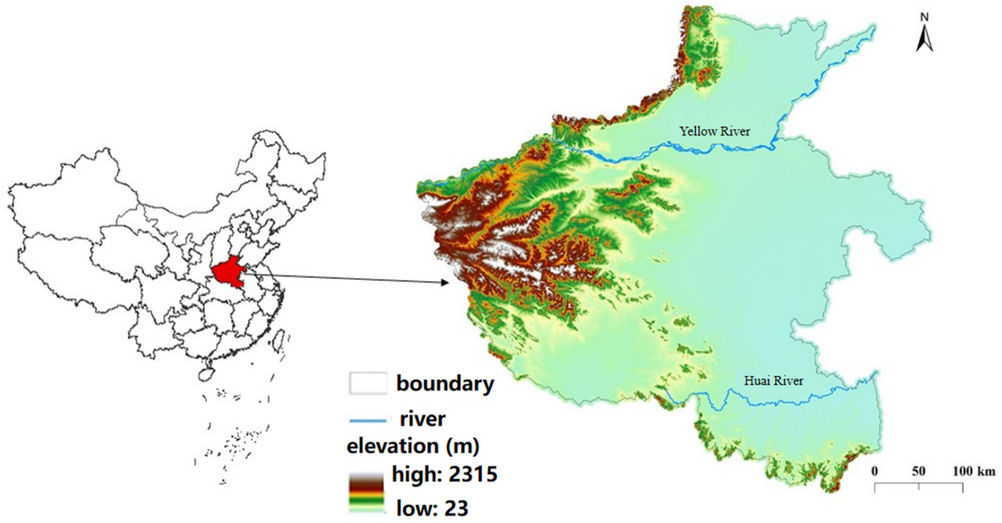

Figure 1. Study area.

The environmental variable data used in this paper, including precipitation (Pre.), evaporation (Eva.), sunshine hours (SH), emissivity (Emi.), and accumulated temperature (AT), were obtained from the National Data Center for Meteorological Sciences. The data format is shown in Table 2. According to modeling requirements, environmental variables were assigned to sampling points in ArcGIS10.7. All the data were resampled based on a one-kilometer grid.

$$\text{Wheat nitrogen yield response (kg/ha)} = \text{Yield}_1 \text{ (kg/ha)} - \text{Yield}_2 \text{ (kg/ha)},$$

where Yield_1 is the yield of wheat under recommended fertilization, and Yield_2 is the yield of wheat under no nitrogen fertilization. The recommended fertilization treatment was the amount given by local agricultural technology extension personnel based on long-term experiments, which were based on the yield goal and soil nitrogen content.

The spike number m^{-2}, grain number per spike m^{-2}, and 1000-grain weight from the sampling survey were used to estimate yield during wheat's mature period. The amount of nitrogen fertilizer used under the local customary fertilization treatment according to the actual wheat production. The wheat yield is calculated as follows.

$$\text{Wheat yield (kg/ha)} = \text{spike number} \times \text{grain number per spike} \times \text{1000-grain weight}$$

The atmospheric nitrogen deposition data in 2010 were from the "Dataset of spatio-temporal pattern of atmospheric inorganic nitrogen dry deposition in China from 2006 to 2015" and "Dataset of spatio-temporal pattern of wet deposition of atmospheric inorganic nitrogen in China from 1996 to 2015" [20,21]. The number of observation sites for wet and dry nitrogen deposition was 1807 and 43, respectively. The dataset was completed by the remote-sensing model based on the measured stations, and the spatial pattern of wet deposition was completed using the spatial interpolation method based on the standardized station data.

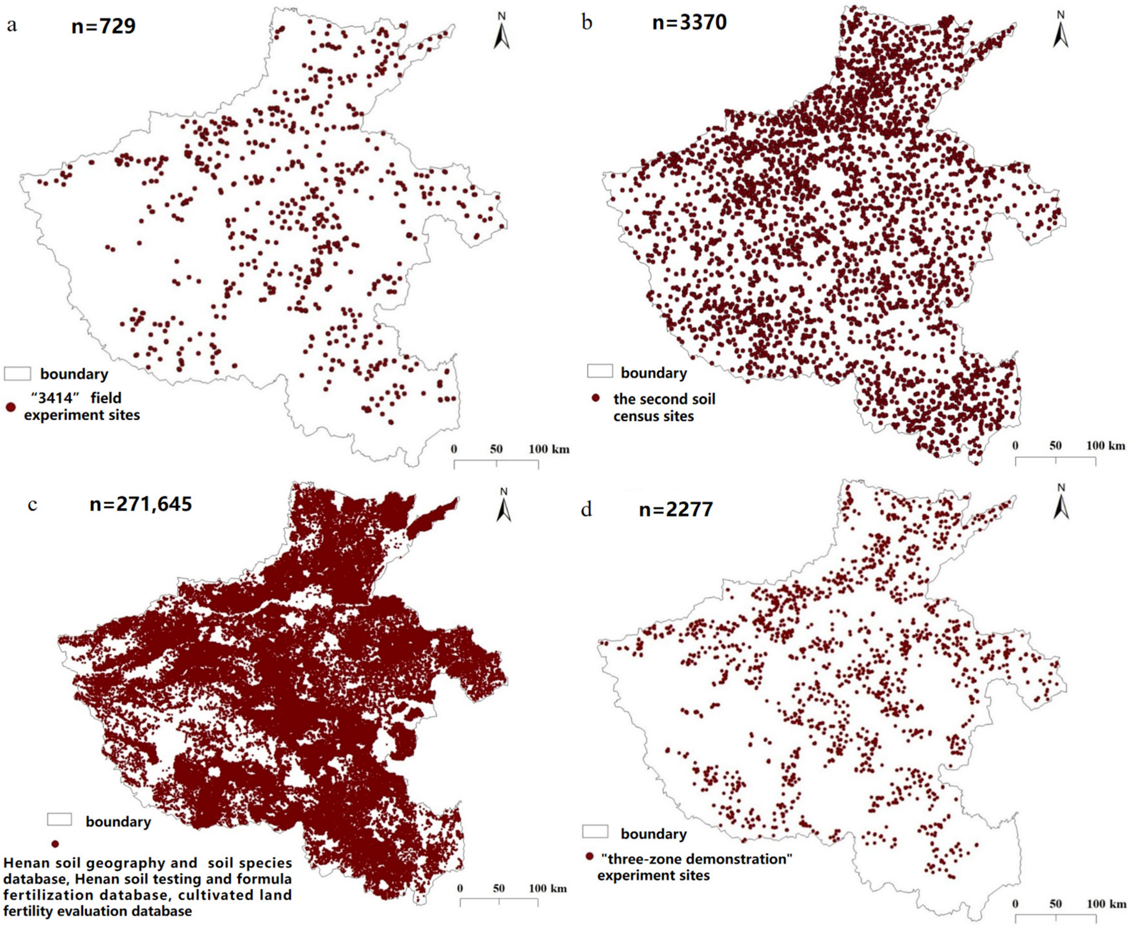

Figure 2. Sampling sites in Henan Province. Note: (**a**) the value of wheat nitrogen yield response was calculated via the "3414" field experiment. (**b**) The value of soil nitrogen content in 1980 was retrieved from the second soil census; (**c**) the value of soil nitrogen content in 2010 was from Henan Province soil geography and soil types, and Henan Province soil testing and formula fertilization and cultivated land fertility evaluation database. (**d**) The value of nitrogen fertilization application was from the "three-zone demonstration" experiment. n is the number of experiment sites.

Table 1. Information related to the soil samples.

Variables	Soil Samples	Source	Year
Wheat yield	729	"3414" field experiment	2010
Soil nitrogen content	3370	The second soil census	1980
Soil nitrogen content	271,645	Henan Province soil testing and formula fertilization and cultivated land fertility evaluation database	2010
Nitrogen fertilization application	2277	"three-zone demonstration" experiment	2010

Table 2. Information related to the environmental variables.

Variables	Abbreviation	Format	Resolution	Source
Precipitation	Pre.	Polygon	1:3,500,000	National Data Center for Meteorological Sciences, 2010
Evaporation	Eva.	Polygon	1:3,500,000	National Data Center for Meteorological Sciences, 2010
Sunshine hours	SH	Polygon	1:3,500,000	National Data Center for Meteorological Sciences, 2010
Emissivity	Emi.	Polygon	1:3,500,000	National Data Center for Meteorological Sciences, 2010
Accumulated temperature	AT	Polygon	1:3,500,000	National Data Center for Meteorological Sciences, 2010

The wheat nitrogen uptake was measured by stem leaf and grain nitrogen content during wheat's mature period under no nitrogen fertilization and recommended nitrogen fertilization. Soil nitrogen supply capacity refers to the wheat nitrogen uptake during wheat's mature period under no nitrogen fertilization. The value reflects the actual nitrogen by wheat absorbed and includes the comprehensive nitrogen from soil, including the nitrogen from irrigation water, rainfall, and biological nitrogen fixation. This method was convenient for direct application in wheat production.

2.3. Data Analysis

SPSS 25 statistical software was utilized for the minimum, maximum, mean, and standard deviation in wheat nitrogen yield response and was analyzed using a correlation analysis between wheat nitrogen yield response and environmental factors. We selected soil pH, organic matter (OM), total nitrogen (TN), available phosphorus (AP), and available potassium (AK) to reflect the soil properties. Soil pH was determined using a pH meter in a 1:2.5 (soil:water) suspension. OM using $K_2Cr_2O_7$-H_2SO_4 was analyzed via the oxidation–reduction colorimetric method. TN was measured using the semi-micro Kjeldahl digestion method. AP was measured with the Molybdenum-antimony colorimetric method using an ultraviolet spectrophotometer at 625 nm, and AK was determined using a flame spectrophotometer.

Random Forest is a common algorithm used in machine learning and has better tolerance to noise and outliers, good parallelism and scalability for high-dimensionality datasets, and high prediction accuracy [22]. Random Forest uses bootstrap technology to randomly select multiple pieces of data from the original samples, then conducts decision tree modeling and obtains the final prediction results through voting. The Random Forest toolkit was used for modeling and prediction. Generally, there are four steps: (1) Read the random Forest algorithm package, library. (2) Import modeling and forecasting datasets, read < -data. (3) Determine the optimal parameters of the Random Forest model. (4) Model establishment and prediction. There are two important parameters in the prediction process, mtry and ntree. Mtry determines the relationship between each classification tree. The larger the value of mtry, the stronger the predictive power of each tree model and correlation. Ntree is the total number of tree models. The accuracy of the algorithm is high with a higher number, but it will affect the program's running speed. In this study, mtry is set as the default value, and ntree is set as 2000 to ensure the robustness of the model [23].

The semivariogram function can describe the randomness and structure of regional variables at the same time and reflect the soil property changes among the distance observations of each point in the region. It is an effective tool for analyzing spatial variation regularity and spatial structure [24]. C0/(C0 + C) is the ratio of nugget value, which represents the spatial correlation and spatial variation. When the value is less than 25%, the spatial correlation is strong, and the spatial variation is mainly caused by structural factors. When the value is between 25% and 75%, the spatial correlation is medium. The random factors and structural factors codetermine the spatial variation. When the value is greater than 75%, the spatial correlation is weak, and the spatial variation is mainly caused by random factors.

The Ordinary Kriging method is based on the theory and structural analysis of the semivariogram function to estimate the value of regional variables in a limited region. The value is estimated by a weighted linear combination of sample points. The model is as follows:

$$Z_0 = \sum_{i=1}^{n} \lambda_i Z(X_i)$$

where Z_0 is the eigenvalue valuation result, λ_i is the weight of eigenvalues obtained by the semivariogram function, $Z(X_i)$ is the measured values, X_i is the location of sample point, and n is the sample point number.

The original data are divided into 80% training and 20% validation sets using the stratified random method. The training set is used for modeling, and the validation set is used for accuracy evaluation. Four indexes, root mean square error (*RMSE*), mean error

(ME), Lin's consistent correlation coefficient (LCCC), and determination coefficient (R^2) are used to evaluate the spatial prediction accuracy of each model. The prediction accuracy of the model increases as the values of $RMSE$ and ME decrease, and the prediction accuracy is related to the dimensionality of the original data. LCCC is an index expressing the consistency between the predicted and measured values of the dependent variable, which can be used to evaluate prediction accuracy. The indexes are as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - M_i)^2}{n}}$$

$$R^2 = \left(\frac{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)(M_i - M)}{\sqrt{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2}\sqrt{\sum_{i=1}^{n}(M_i - M)^2}}\right)^2$$

$$ME = \frac{1}{n}\sum_{i=1}^{n}(O_i - M_i)$$

where O_i is the measured value, M_i is the predicted value, $\bar{O}$ and M are the means of the predicted and measured values, respectively, and n is the sample point number.

The correlation analysis among maps was implemented in ArcGIS 10.7. The gray value of the corresponding raster layer in the same area was analyzed to judge the changing trend of variables. The correlation coefficient matrix between raster layers was exported using the band collection statistics function.

3. Results

3.1. The Characteristics of Statistics and Spatial Variation of Wheat Nitrogen Yield Response

Compared with no nitrogen fertilization, the wheat yield was significantly increased by 32% under the recommended fertilization, and the average wheat nitrogen yield response was 1662 kg/ha (Table 3). There was no significant correlation between wheat nitrogen yield response and wheat yields under low, medium, and high-yield levels, respectively (Figure 3), but there was a significant difference under different soil types. The wheat nitrogen yield response was highest in paddy soil, 2.84 times that in yellow-brown soil (Figure 4).

Table 3. Statistical characteristics of wheat yield and wheat nitrogen yield response in Henan Province.

Fertilization Treatments	Number	Minimum Yield (kg/ha)	Maximum Yield (kg/ha)	Average Yield (kg/ha)	Standard Error
No nitrogen	729	1871	8772	5219	52
Recommended nitrogen	729	2393	10,467	6881	46
Wheat nitrogen yield response	729	528	4887	1662	37

The accuracy of the model was evaluated according to the hierarchical random principle. The correlation between the predicted and the measured value was significant ($p < 0.05$), which indicated that the model could be used to predict wheat yield in Henan Province (Figure 5). The spatial distribution of the wheat nitrogen yield response using the Random Forest method is shown in Figure 6. The wheat nitrogen yield response changed significantly throughout the entirety of Henan Province, where the maximum value was 4887 kg/ha and the minimum value was 522 kg/ha. The wheat nitrogen yield response was mainly concentrated around 1300–2400 kg/ha. The highest value was observed in the southern, southwestern, and eastern regions and the lowest in the northern and western regions.

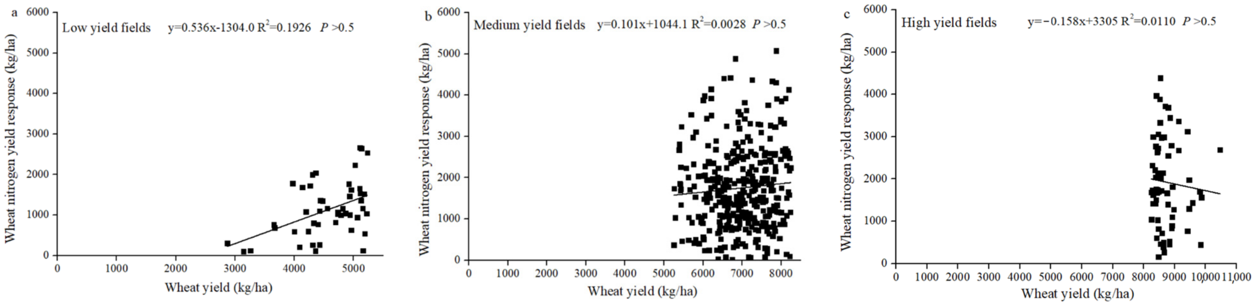

Figure 3. The correlation analysis between wheat nitrogen yield response and wheat yield. Note: (**a**) low-yield fields (wheat yield ≤ 5250 kg/ha); (**b**) medium-yield fields (5250 kg/ha < wheat yield < 8250 kg/ha); (**c**) high-yield fields (wheat yield ≥ 8250 kg/ha).

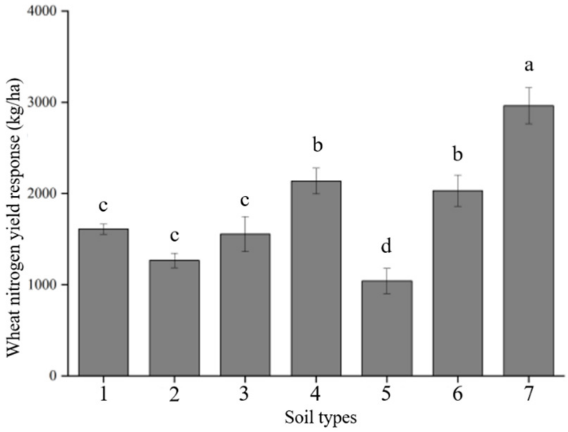

Figure 4. Statistical characteristics of wheat nitrogen yield response under different soil types. Note: 1: fluvo-aquic soil; 2: cinnamon soil; 3: red clay; 4: yellow cinnamon soil; 5: yellow-brown soil; 6: lime concretion black soil; 7: paddy soil. Values followed by different letters significantly differ at the 0.05 probability level under different soil types.

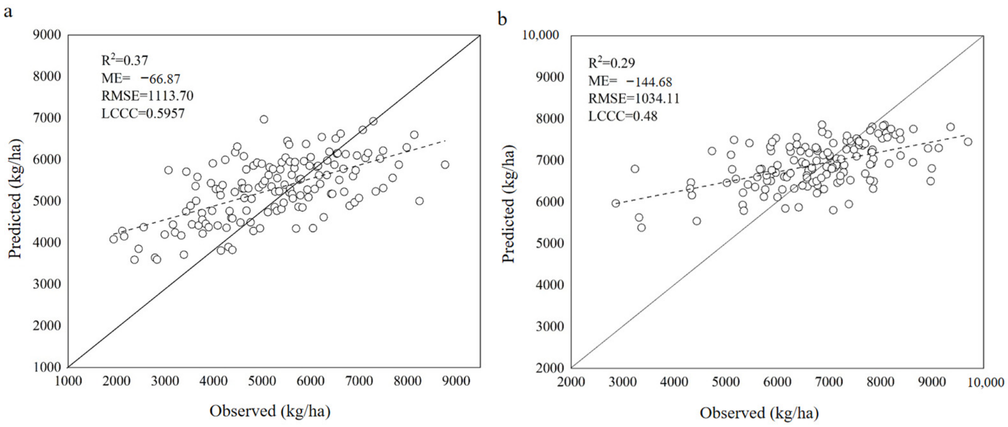

Figure 5. The accuracy evaluation of the Random Forest model. Note: (**a**) wheat yield under no nitrogen fertilization; (**b**) wheat yield under recommended fertilization.

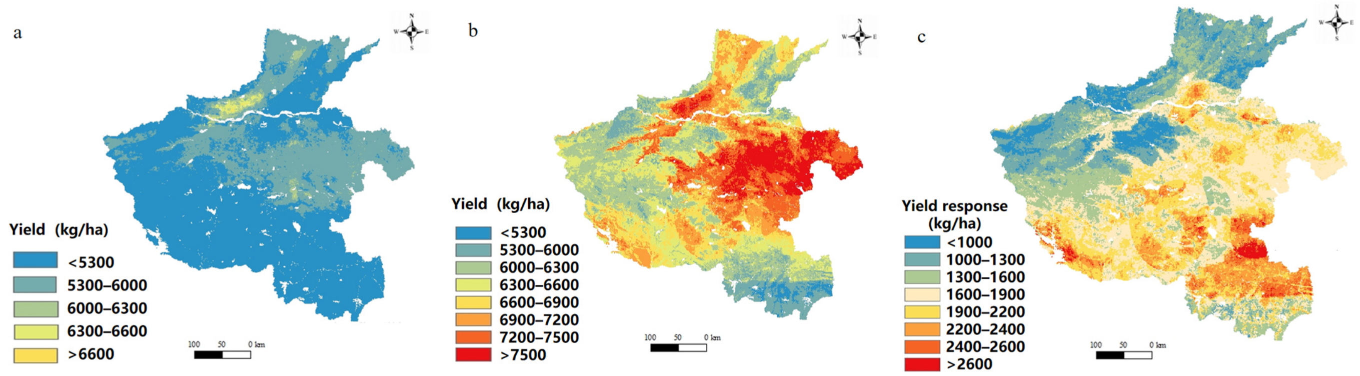

Figure 6. Spatial distribution characteristics of wheat yield and wheat nitrogen yield response. Note: (**a**) wheat yield under no nitrogen fertilization; (**b**) wheat yield under recommended fertilization; (**c**) wheat nitrogen yield response.

3.2. The Spatial Variation of Soil Nitrogen

The spatial distribution of soil nitrogen content had the same trend between 1980 and 2010 (Figure 7). The spatial distribution of soil nitrogen was 0.25–1.40 g/kg in 1980 and 0.65–1.30 g/kg in 2010. The soil nitrogen was highest in the western and southern regions and was lowest in the eastern region. From 1980 to 2010, soil nitrogen increased significantly in the eastern, southwestern, and southern regions from 0.20 to 0.50 g/kg. There was no significant correlation between the wheat nitrogen yield response and soil nitrogen content at different levels (Figure 8).

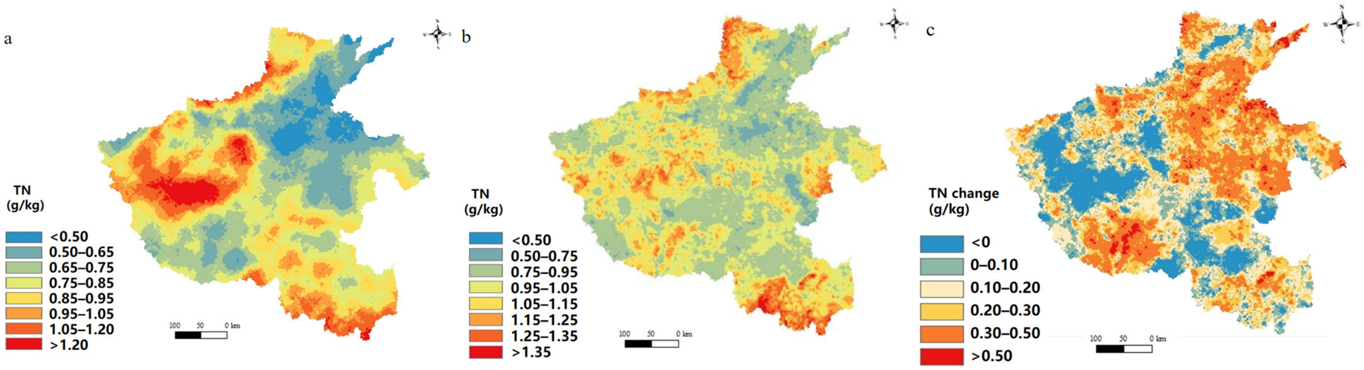

Figure 7. Spatial distribution characteristics of soil nitrogen content. Note: (**a**) TN in 1980; (**b**) TN in 2010; (**c**) TN change from 1980 to 2010. TN: soil total nitrogen.

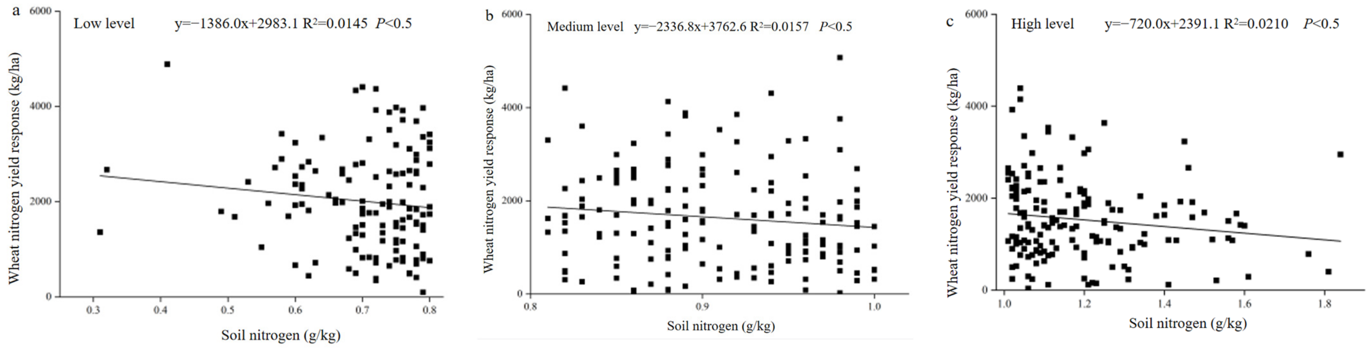

Figure 8. The correlation analysis between the wheat nitrogen yield response and soil nitrogen content. Note: (**a**) low soil nitrogen level; (**b**) medium soil nitrogen level; (**c**) high soil nitrogen level.

3.3. Nitrogen Fertilization

Figure 9 shows the spatial distribution of nitrogen fertilization. Nitrogen fertilization showed no significant differences across Henan Province. The nitrogen fertilization values ranged from 158 to 203 kg N/ha and were mainly concentrated around 173–203 kg N/ha. The highest value was observed in the northern and eastern regions, and the lowest was in the southwestern region.

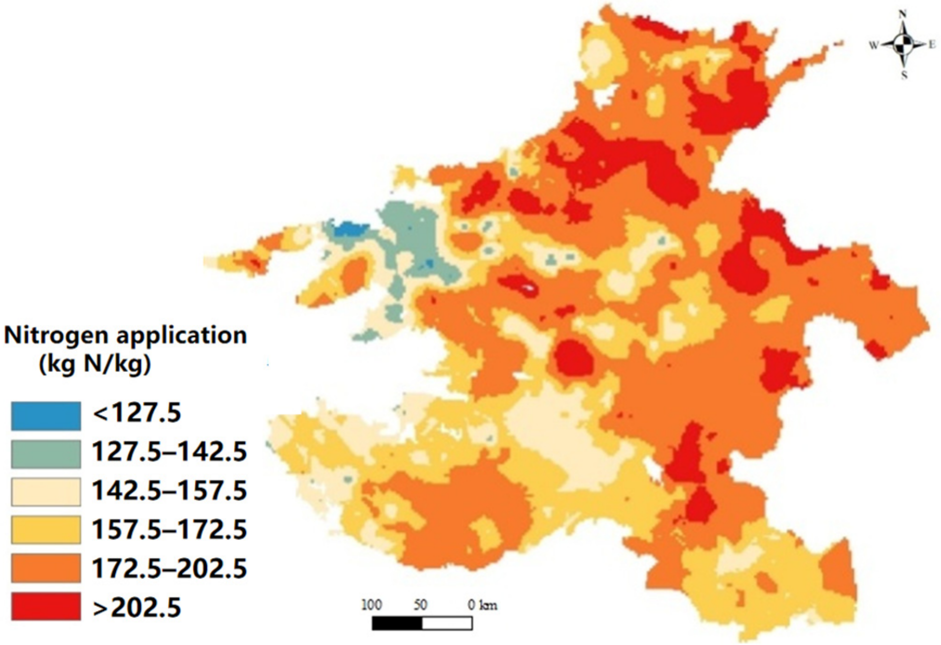

Figure 9. Spatial distribution characteristics of nitrogen fertilization.

3.4. Nitrogen Deposition

Figure 10 shows the spatial distribution characteristics of wet and dry nitrogen deposition in Henan Province. The highest values of wet and dry nitrogen deposition were observed in the northern region, and the lowest values were observed in the southwestern and southern regions. The wet nitrogen deposition ranged from 15 to 39 kg N/(ha yr), and the dry nitrogen deposition ranged from 7 to 49 kg N/(ha yr). The average values of wet and dry nitrogen deposition were both 15 kg N/(ha yr).

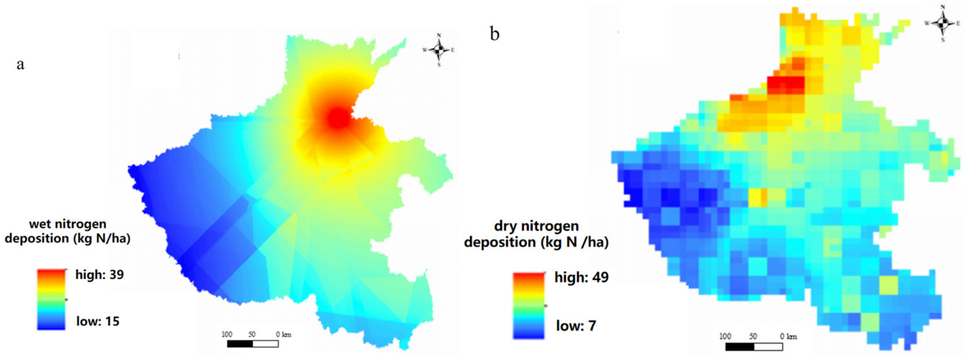

Figure 10. Spatial distribution characteristics of soil nitrogen deposition per year. Note: (**a**) wet nitrogen deposition; (**b**) dry nitrogen deposition.

3.5. Soil Nitrogen Supply Capacity and Wheat Nitrogen Uptake

The spatial distribution of the soil nitrogen supply capacity and wheat nitrogen uptake under the recommended nitrogen fertilization had the same trend (Figure 11). The highest value was observed in the eastern region, and the lowest was in the southern region. The soil nitrogen supply capacity and wheat nitrogen uptake was mainly concentrated around

105–150 kg N/ha and 2.2–2.6 kg/100 kg, respectively. As seen in Table 4, precipitation and temperature had a notable positive correlation with the soil nitrogen supply capacity.

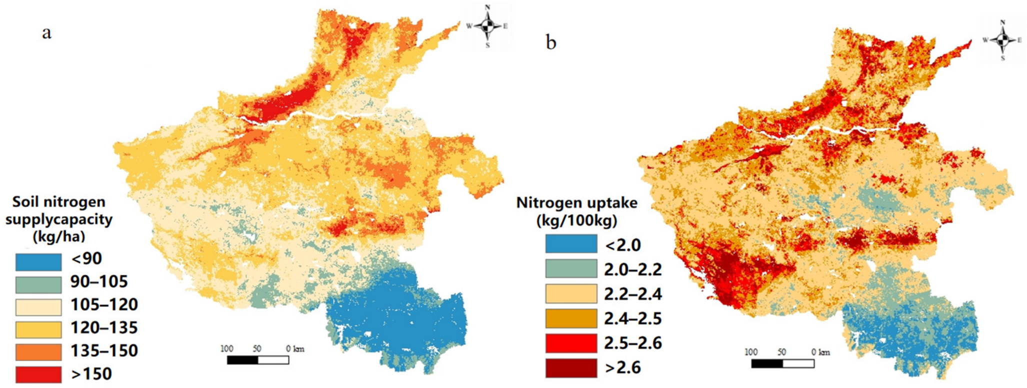

Figure 11. Spatial distribution characteristics of soil nitrogen supply capacity and wheat nitrogen uptake. Note: (**a**) soil nitrogen supply capacity; (**b**) wheat nitrogen uptake under recommended nitrogen fertilization.

Table 4. The correlation coefficient between soil nitrogen supply capacity and environmental factors in the eastern region.

Pre.	Eva.	SH	Emi.	AT
0.364 **	−0.057	−0.270 **	0.015	0.249 **
pH	OM	TN	AP	AK
−0.248 **	−0.148 **	−0.113 **	0.031	−0.183 **

Note: Pre.: precipitation; Eva.: evaporation; SH: sunshine hours; Emi.: emissivity; AT: accumulated temperature; OM: organic matter; TN: total nitrogen; AP: available phosphorus; AK: available potassium. "**" indicate significant differences at 0.01 levels.

4. Discussion

4.1. Multiple Reasons for Spatial Variation in Wheat Nitrogen Yield Response

Nitrogen fertilization plays a very important role in improving wheat yields [25–27]. The wheat nitrogen yield response can reflect the relationship between the wheat yield and nitrogen fertilizer per unit area. Our results showed that the wheat yield had a significant influence on nitrogen fertilizer in the experiment, and we assumed that the soil nitrogen content could be the most influential factor [28]. From 1980 to 2010, soil nitrogen content increased by 21%. The average wheat nitrogen uptake was 165 kg/ha (2.4 kg/100 kg × 6881 kg/ha) in 2010, and the soil nitrogen content increased by 345 kg/ha. The increase in soil nitrogen far exceeded wheat needs, which indicated that the spatial variation of soil nitrogen content was significantly correlated with 30 years of high nitrogen fertilizer management. Compared with the spatial distribution of the wheat nitrogen yield response, we found that there was no significant, direct correlation with the soil nitrogen content, e.g., the wheat nitrogen yield response was highest in the southwestern and eastern regions, while the soil nitrogen content was highest in the northern and southern regions. Therefore, the soil nitrogen content was not a critical factor in the wheat nitrogen yield response. Combined with correlation analysis, we found that the wheat nitrogen yield response was not significantly correlated with different soil nitrogen content levels, which also indicated that the soil nitrogen yield response could not be measured by different levels under the relative saturation of soil nitrogen. The spatial variability in soil nitrogen content had no significant correlation with nitrogen fertilization management. The reason for this was that the soil nitrogen content mainly depended on the parent land topography and soil types [29]. The average value of the soil nitrogen content was 0.98 g/kg in 2010, which was under the middle level, so optimal nitrogen fertilizer management should also be considered during wheat growth [8,30]. We should adapt nitrogen fertilization amounts to soil factors and wheat demand, which would not only improve nitrogen fertilizer use efficiency, but also reduce nitrogen environmental pollution [2,11,31]. The wheat nitrogen yield response was also affected by nitrogen deposition, but it calculated that the contribution of nitrogen deposition was only 7.5 kg N/ha during wheat growth stages [20,21], which was far less than the soil nitrogen supply capacity (105–135 kg N/ha). Compared with the spatial distribution of the wheat nitrogen yield response, we found that wheat yield and soil nitrogen supply capacity had the same trend in the eastern region. In this region, the soil type was mainly fluvo-aquic soil, which was formed by Yellow River alluvium, and wheat yield and soil nitrogen supply capacity were mainly affected by precipitation and temperature. During wheat production, an increase in precipitation could promote water and nitrogen metabolism in wheat, which is conducive to the synthesis of nutrients and the accumulation of photosynthetic products in the grain, improving the wheat yield and protein content [32]. The nitrogen yield response was the highest in paddy soil with higher nitrogen fertilization management and soil nitrogen content, which indicated that the soil nitrogen supply capacity was low in paddy soil. Compared to fluvo-aquic soil and paddy soil, we found that the soil types also affected the nitrogen yield response, which might be related to different soil textures and nitrogen mineralization rates. When the soil nitrogen supply capacity was strong, the nitrogen conversion efficiency in the region was high, and the wheat yield increased significantly [30]. The soil nitrogen supply capacity and wheat nitrogen uptake were used to represent soil nitrogen mineralization. In the southern region of Henan Province (mainly paddy soil), the soil nitrogen mineralization rate was low, but the wheat nitrogen yield response and soil nitrogen content were high. The correlation between the soil nitrogen mineralization rate and the wheat nitrogen yield response was weak, which indicated that the region featured high nitrogen with a low-yield field. We should pay more attention to management technology to improve the wheat's ability to absorb soil nitrogen in this region. In the eastern region of Henan Province (mainly fluvo-aquic soil), the soil nitrogen mineralization rate and wheat nitrogen yield response were high, but the soil nitrogen content was low. The correlation between the soil nitrogen mineralization rate and the wheat nitrogen yield response was strong, which indicated that the region featured low nitrogen with a high-yield field. In order to maintain high soil fertility, we should pay more attention to nitrogen supplementation in high-yield fields rather than simply dividing high-yield fields and reducing nitrogen fertilizer application.

The level of soil nitrogen content increased significantly in the past 30 years, which indicated that there was a general enrichment in nitrogen on farmland. In Henan Province, the variation in soil nitrogen significantly differed among regions, with an obvious increase in the eastern, southwestern, and southern regions, especially in fluvo-aquic soil and paddy soil. Based on the spatial and temporal variation characteristics of soil nitrogen in Henan Province, it is recommended that different regions adopt tailored nitrogen fertilization-management practices. The strong mineralization rate of the fluvo-aquic soil region is an important basis for wheat nitrogen uptake for production, and the main driving factor is precipitation and temperature. Thus, the amount of nitrogen fertilizer application is equal to the soil nitrogen supply in this region, which is about 120–150 kg/ha. The weak mineralization rate capacity of paddy soil results in the accumulation of residual nitrogen in the topsoil layer, particularly when a substantial amount of nitrogen is applied in wheat production. Thus, the amount of nitrogen fertilizer application should equal the wheat nitrogen uptake, which is about 150 kg/ha. Based on the actual nitrogen fertilizer application (about 200 kg/ha), we suggest reducing nitrogen fertilization by 50 kg/ha in the paddy soil region.

4.2. The Main Factors Influencing the Soil Nitrogen Mineralization Rate

Compared with the wheat nitrogen yield response distribution map, the soil nitrogen supply capacity and wheat nitrogen uptake could reflect its spatial variability. The soil nitrogen supply capacity could be used to represent the soil nitrogen mineralization rate. The soil nitrogen mineralization rate was higher in the areas with low nitrogen with high yield fields, which was related to geographical conditions, such as loose soil, good light conditions, good temperature, and low precipitation [33]. We also found that the nitrogen content and wheat nitrogen yield response in the high yield fields were low, but the soil mineralization rate was high. Due to the soil's high mineralization rate, a significant amount of soil organic nitrogen was consumed, and the soil fertility was improved with high soil nitrogen content [34]. A lot of nitrogen was absorbed by the wheat, which increased the yield rapidly [7,25]. The soil nitrogen mineralization rate significantly varied under different soil types, especially fluvo-aquic and paddy soil. The soil nitrogen mineralization rate was affected by precipitation and soil temperature due to the differences in nitrogen release [35], which directly affected wheat yields [36]. High temperatures and water deficit could depress the development of spikes and seeds, leading to a remarkable yield reduction [32]. Therefore, we could improve the soil nitrogen mineralization rate by regulating soil moisture under different soil types.

5. Conclusions

Using machine learning and map comparison methods, we identified influential factors of the wheat nitrogen yield response in Henan Province. The wheat nitrogen yield response was mainly concentrated around 1300–2400 kg/ha in Henan Province, with the highest values observed in the southern and eastern regions. We determined that the soil nitrogen supply capacity was pivotal in influencing the nitrogen yield response. The eastern region showed low nitrogen levels but high yields, suggesting the necessity to supplement nitrogen fertilizer based on the soil nitrogen supply capacity to maintain the soil fertility balance, which was about 120–150 kg/ha. The southern region exhibited high nitrogen levels but low yields, indicating the need to reduce nitrogen fertilizer application based on wheat nitrogen uptake and regulate soil moisture to improve the soil nitrogen mineralization rate. Thus, we suggest reducing nitrogen fertilization application by 50 kg/ha in the paddy soil region. As a result, nitrogen fertilizer management should prioritize the soil nitrogen supply capacity and wheat nitrogen uptake rather than solely relying on the soil nitrogen content during the wheat growth stage.

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