RESEARCH ARTICLE

A study on the spatiotemporal variation of nitrogen fertilization rationality in winter wheat based on the synergistic mechanism of "crop-farmland-environment"

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Nitrogen (N) fertilizer plays a critical role in sustaining high grain yields, but its overuse in intensive agricultural systems has led to environmental pollution and reduced fertilizer efficiency. Addressing the spatial heterogeneity of N application is essential for achieving precision agriculture and sustainable development. This study evaluated the rationality of N fertilizer application for winter wheat in Henan, China from 2005 - 2009 to 2015 - 2019 based on a synergistic mechanism integrating crop demand, farmland soil conditions, and environmental impacts. By using geostatistical methods, spatial interpolation, and a nitrogen balance model, this study analyzed soil total nitrogen (TN) dynamics, estimated theoretical N application rates, and assessed fertilization rationality across the study area. The results showed that TN increased from an average of 0.96 g/kg in 2009 to 1.05 g/kg in 2019, indicating a steady-state farmland system. In 2019, 77.38% of the cultivated area achieved rational N application, while 22.61% still exhibited over- or under-fertilization. A spatially optimized fertilization plan was developed by using map algebra, which could reduce N fertilizer use by approximately 4.247 × 10^7 kg, equivalent to 9.233 × 10^7 kg of urea, generating direct economic benefits of about ¥185 million (CNY). This research provided a scientific basis for region-specific N management strategies, contributing to food security and environmental protection in major grain-producing areas.

Keywords: crop-farmland-environment; synergy; winter wheat; nitrogen fertilizer; rationality assessment; spatial optimization.

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Introduction

In 2025, China's grain output reached 7.15×10^{11} kg [1], demonstrating that approximately 9% of the world's arable land supports nearly 20% of the global population [2]. Among all production inputs, synthetic N fertilizer is pivotal, contributing 45% to national grain yield [3]. Nevertheless, China's annual N consumption exceeds 30 million tons, accounting for 30% of the global total. Despite sustaining high yields, this intensive N use has concurrently diminished the marginal productivity of additional fertilizer applications and exacerbated non-point-source pollution [4, 5]. Consequently, characterizing the spatiotemporal patterns of N application rationality is a prerequisite for developing site specific N reduction strategies. Research on N fertilizer management for winter wheat has advanced substantially across multiple domains.

In terms of application techniques, optimizing fertilizer timing [6], adjusting nutrient ratios and placement [7, 8], and improving fertilizer formulations [9] have been demonstrated as effective approaches to enhance nitrogen use efficiency. Regarding the relationship between nitrogen application rates and crop yield, numerous field experiments have shown that winter wheat grain yield increases significantly with nitrogen application within a certain threshold, but the yield enhancing effect diminishes or even becomes negative beyond the optimal range [10]. Meanwhile, nitrogen application rates also exert a clear influence on winter wheat grain quality [11].

Crop nitrogen demand is not a fixed value but is significantly modulated by variety characteristics [12], climatic conditions [13], soil fertility, and cultivation management [14]. Consequently, recommended nitrogen application rates derived from localized trials have inherent limitations when extrapolated across regions with diverse agroecological conditions. In recent years, research perspectives on the effects of nitrogen fertilization have gradually shifted from a singular focus on crop agronomic response to more complex agroecosystem processes. An in depth understanding of climate–soil–crop systems and soil–plant–microbe interactions provides new insights for improving nitrogen use efficiency while accounting for ecological impacts [15]. Concomitantly, the integration of enhanced-efficiency fertilizers with conservation tillage, variable-rate application, and canopy reflectance guided side dressing has gained traction [16]. Technologically, the integration of remote sensing monitoring [17], geographic information systems (GIS) [18], and process models-augmented by machine learning algorithms such as random forests [19] offers powerful tools for precise regional nitrogen management and for investigating environmental costs and synergistic benefits. Despite these advances, most studies optimize either agronomic or environmental performance but rarely both simultaneously. The "crop–farmland–environment" synergy integrating crop potential, soil resource endowment, and environmental boundaries remains underexplored. Site-specific experiments dominate, limiting the translation of plot-level insights to regional scales. Furthermore, static assessments overlook the spatiotemporal dynamics of soil nitrogen and its reciprocal relationship with fertilization practices. A coherent technical chain from mechanistic diagnosis to spatial optimization is still lacking, constraining the operational deployment of precision N reduction strategies that balance food security and ecological integrity. Therefore, it is urgently necessary to develop rational nitrogen evaluation and optimization methods from a system synergy perspective, which integrate spatial heterogeneity and balance both food security and ecological safety.

To address these knowledge gaps, this study developed a systematic framework for diagnosing and optimizing the rationality of nitrogen application within the “crop–farmland–environment” synergistic system. By using multi-source field trial datasets across Henan, China, the spatiotemporal dynamics of soil TN were characterized through the geostatistical interpolation and random forest modeling. A theoretical nitrogen application rate was established based on the nitrogen balance principle, which was parameterized with nutrient omission trial data. A diagnostic indicator defined as the ratio of actual to theoretical application rates was employed to classify fertilization rationality into five tiers with a 20% deviation tolerance to account for spatiotemporal variability. Map algebra was then applied to formulate site-specific spatial optimization plans, thereby enabling the quantification of associated economic benefits. By establishing a coherent “mechanistic diagnosis–status assessment–spatial optimization” research framework, this study provided actionable guidance for precision nitrogen reduction in Henan, China and analogous agroecological zones across the Huang–Huai–Hai Plain, while simultaneously safeguarding regional food security and ecological integrity.

Materials and methods

Study Area

Henan, China (31°23′-36°23′ N, 110°21′-116°39′ E) encompasses 1.67×10^5 km², accounting for 1.73% of China's terrestrial area. It is the country's dominant winter wheat producer, routinely supplying over 25% of national output. The climate transitions from warm temperate in the north to northern subtropical in the south, driven by a continental monsoon regime. The mean annual temperature ranges from 12.7 to 16.2°C, and annual precipitation from 478 to 1,167 mm. Topography declines from west to east with mountains and hills occupying 44.3% of the province and plains accounting for 55.7%. The prevailing cropping system is an intensive winter wheat-summer maize rotation.

Three-zone demonstration trial dataset

Field experiments with winter wheat (*Triticum aestivum* L.) were conducted in three distinct agroecological zones of Henan, China during two periods of 2005 – 2009 and 2015 – 2019. The selected sites represented the major wheat producing areas with varying topographic and climatic conditions. Zone A was in Xinxiang, Henan, China (35.18°N, 113.85°E), representing the northern plain, while Zone B in Zhoukou, Henan, China (33.62°N, 114.63°E) represented the central agricultural region; and Zone C in Nanyang, Henan, China (32.99°N, 112.53°E) represented the southern hilly area. Detailed agronomic and management data were collected from demonstration zones within each site. The dataset included 2,249 sampling points for 2005 - 2009 and 2,180 points for 2015 - 2019, recording N, P_2O_5, and K_2O application rates for control (CK), conventional fertilization (CF), and formulated fertilization (FF) treatments, along with winter wheat yields. Data were obtained from the Henan Provincial Soil Testing and Formulated Fertilization Project (http://www.hnsoilfertility.cn). N application rates were interpolated by using ordinary kriging in ArcGIS 10.7 (https://www.esri.com) to generate 30 m resolution raster data. Yields were spatially predicted using a random forest model with covariates including climate, topography, soil properties, and management practices.

Soil fertility survey geochemical dataset

Soil samples from 0 - 20 cm depth were collected from 6,168 points in 2005 - 2009 and 4,425 points in 2015 - 2019, concurrent with the demonstration trials. Samples were taken after autumn harvest and before base fertilizer application, mixed from 15 - 20 subpoints per location. Total nitrogen content was analyzed by using the Kjeldahl method. Data were sourced from the Henan Soil Fertility Monitoring Network (http://www.hnsoilmonitor.cn). Ordinary kriging was applied to interpolate TN to 30 m resolution rasters.

Five-zone nutrient omission trial dataset

A total of 678 site-year records were obtained from provincial omission trials conducted at five locations of Xinxiang (35.18°N, 113.85°E), Zhoukou (33.62°N, 114.63°E), Nanyang (32.99°N, 112.53°E), Shangqiu (34.41°N, 115.65°E), and Luoyang (34.62°N, 112.45°E). Each site included five microplots as full fertilization (NPK), minus-N (PK), minus-P (NK), minus-K (NP), and absolute control. Grain yield, straw yield, fertilizer rates, and plant N concentrations were measured. Nitrogen uptake per 100 kg grain (N_{100}) was calculated as below.

$$N_{100} = \mathrm{N\_grain} \times \frac{\text{straw yield}}{\text{grain yield}} \times 100 \qquad (1)$$

where N_grain was N concentration in grain (kg/kg). N_{100} was interpolated by using ordinary kriging in ArcGIS 10.7.

Estimation of theoretical nitrogen application rate

In a cultivated land grain production system that had reached a long-term steady state under continuous cultivation and straw return, the nutrient inputs and outputs were balanced. The primary nutrient sources included fertilizer application and other natural inputs such as atmospheric deposition, biological nitrogen fixation, and nutrients from irrigation water. Nutrient outputs consisted of crop uptake and removal at harvest, as well as various environmental losses (such as leaching and volatilization. This mass balance was expressed as follows.

$$\text{Fertilizer nutrient input} + \text{Other nutrient inputs} = \text{Crop grain nutrient uptake} + \text{Environmental losses} \quad (2)$$

The theoretical fertilizer application rate was derived from this balance as the amount needed to meet crop demand after accounting for other inputs and unavoidable losses and was calculated as below.

$$\text{Theoretical fertilizer input} = \text{Crop grain nutrient uptake} + \text{Environmental losses} - \text{Other nutrient inputs} \quad (3)$$

Although the specific values for each component varied significantly across different regions and even among fields within the same region, a generalized pattern could be widely observed and adopted in practice as “The reasonable nitrogen application rate was approximately equal to the above-ground nitrogen uptake of the crop” [20]. The underlying rationale for this pattern was that, in a steady-state system with straw return, the combined contribution from non-fertilizer nitrogen sources was typically insufficient to fully compensate for all nitrogen losses to the environment. The resulting nitrogen deficit was roughly equivalent to the nitrogen content retained in the crop straw. Consequently, the theoretical nitrogen application rate could be practically estimated as a function of crop yield and the crop's nitrogen uptake efficiency as follows.

$$T\text{heoretical N application rate (kg/ha)} = [\text{Crop yield (kg/ha)} /100] \times \text{N uptake per 100 kg of grain (kg)} \quad (4)$$

Rationality assessment of nitrogen application

To quantitatively evaluate the rationality of actual fertilization practices, a diagnostic indicator R was defined as the ratio of the actual fertilizer nutrient input to the theoretically estimated application rate as follows.

$$\text{R} = \text{Actual fertilizer nutrient input}/ \text{Theoretical application rate} \quad (5)$$

Based on this ratio, the rationality of fertilization was classified according to predefined thresholds. An R value of approximately 1.0 indicated a balanced nutrient supply, where any environmental impact was attributable to unavoidable nutrient losses under current management practices. Values of R greater than 1.0 suggested excessive fertilization, which might lead to unnecessary nutrient accumulation and increased environmental pollution risk. Conversely, an R value less than 1.0 indicated insufficient fertilization. While this might reduce immediate environmental risks, it could deplete soil nutrient reserves and negatively affect crop yield and quality over time. Given the inherent spatial and temporal variability in crop growth, soil properties, and environmental conditions, the theoretical application rate was not treated as a single fixed value but rather as a reference baseline. To account for these uncertainties and measurement errors, a tolerance range around R = 1.0 was established. For this study, a deviation of 20% from the theoretical rate was adopted as the acceptable range for rational fertilization. This threshold was determined based on the accuracy of field sampling, laboratory analysis, and model estimation, and was consistent with the variability observed in intensive high-yield wheat production systems. Accordingly, the rationality of nitrogen fertilization for winter wheat in the study area was diagnosed by using the classification criteria, where the ratio R served as the quantitative evaluation basis, in which $R \le 0.60$ indicated severely insufficient fertilization, $0.60 < R \le 0.80$ represented insufficient fertilization, $0.80 < R \le 1.20$ suggested rational fertilization, $1.20 < R \le 2.00$ represented excessive fertilization, and $R > 2.00$ indicated severely excessive fertilization.

Statistical analysis

Model performance for spatial interpolation was evaluated by using Pearson correlation coefficient (R^2), mean absolute error (MAE), root mean square error (RMSE), and normalized RMSE

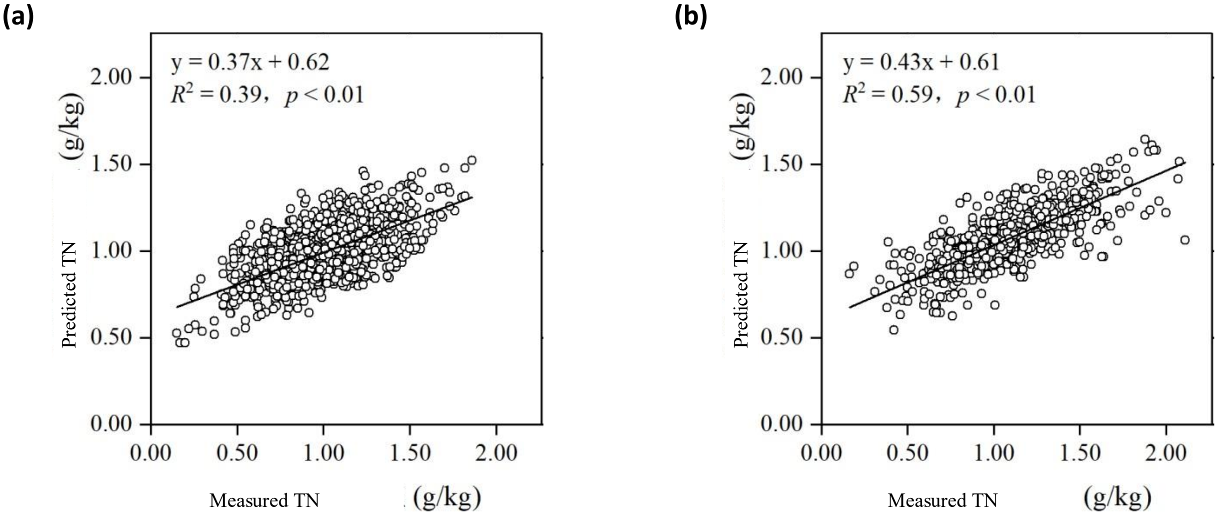

Figure 1. Comparison between the measured and predicted TN during the periods 2005 – 2009 (**a**) and 2015 – 2019 (**b**).

(NRMSE). All statistical analyses were performed in R software (version 4.2.1) (https://www.r-project.org). Variogram modeling and kriging were conducted by using the "gstat" package in R. *P* value less than 0.05 was defined as statistically significant.

Results and discussion

Spatiotemporal dynamics of TN

The spatial distribution of TN across the study area was characterized by two sampling periods of 2005 - 2009 and 2015 - 2019 using geostatistical analysis. Normality tests confirmed that TN data for both periods followed a normal distribution, satisfying the underlying assumptions for Kriging interpolation. Experimental variograms were calculated directly from the original TN measurements and fitted using theoretical models. The spatial structure of TN quantified by the proportion of structural variance ($C / (C_0 + C)$) exhibited notable changes over the decades. During 2005 - 2009 period, the structural variance proportion was 32.13%, indicating that spatial variability was primarily influenced by stochastic anthropogenic factors such as heterogeneous farming practices among individual households. By 2015 - 2019 period, this proportion had increased to 47.24%, suggesting a trend toward more uniform field management across the region. Based on the fitted variogram models, ordinary Kriging interpolation was employed to predict TN across the study area. Cross-validation of the interpolation results demonstrated satisfactory predictive accuracy (Figure 1). For 2005 - 2009 dataset, validation yielded an R^2 of 0.39 ($P < 0.01$), a MAE of 0.16 g/kg, a RMSE of 0.20 g/kg, and a NRMSE of 20.86%. For 2015 - 2019 dataset, the corresponding metrics improved to R^2 of 0.59 ($P < 0.01$), MAE of 0.14 g/kg, RMSE of 0.19 g/kg, and NRMSE of 18.22%, reflecting the enhanced spatial structure and data consistency in the later period. To facilitate interpretation of agronomic significance, TN content was classified into four grades based on practical productivity thresholds including ≤ 0.75 g/kg (low), 0.75 - 1.00 g/kg (moderately low), 1.00 - 1.25 g/kg (moderately high), and > 1.25 g/kg (high). The spatial distribution and proportional area of each grade demonstrated that, in 2005 - 2009, TN content ranged from 0.54 to 1.52 g/kg with a mean value of 0.96 g/kg. The 0.75 - 1.00 g/kg grade dominated the landscape, occupying 60.08% of the total cultivated area. Areas with TN ≤ 0.75 g/kg were predominantly concentrated in the Huang-Huai-Hai Plain region, while areas exceeding 1.25 g/kg were primarily associated with specific soil types including paddy soils in

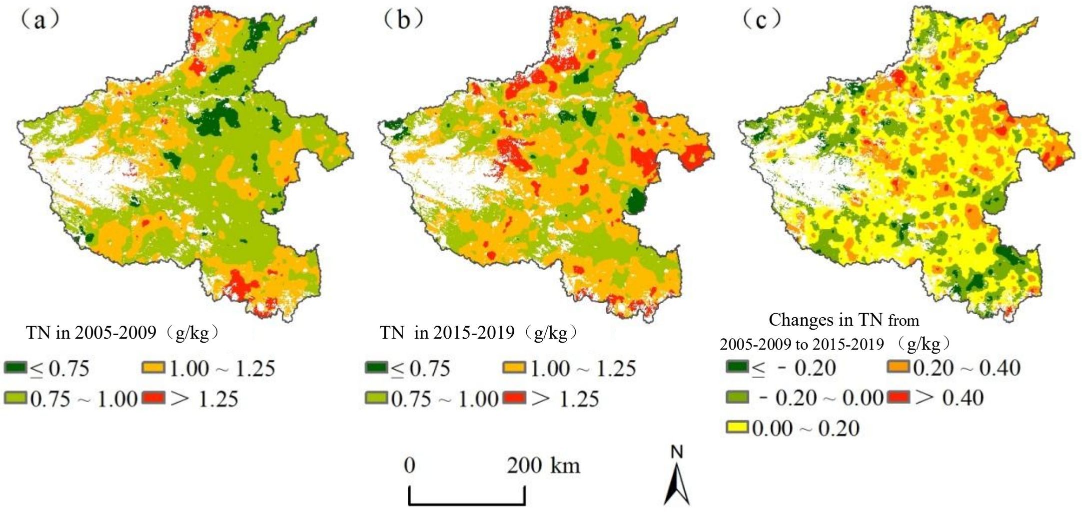

Figure 2. Spatial prediction results of TN based on ordinary Kriging. (**a**) 2005 – 2009. (**b**) 2015 – 2019. (**c**) the changes between two periods.

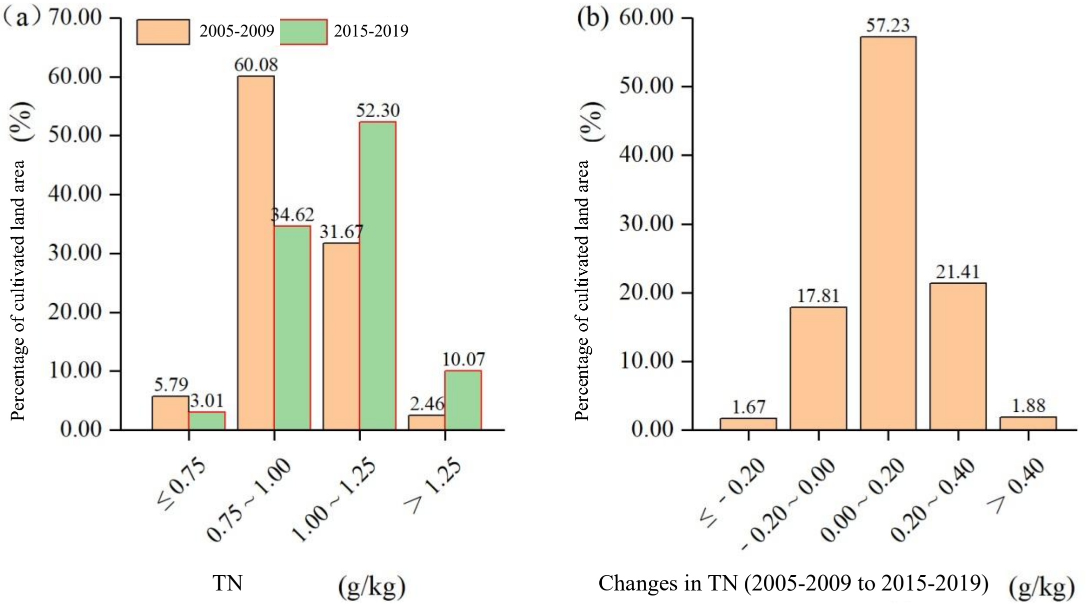

Figure 3. Area percentage of different grades of TN (**a**) and TN changes (**b**).

southern Henan and skeletal soils in the northern part of the study area. By 2015 - 2019, TN content had increased, ranging from 0.54 to 1.78 g/kg with a mean of 1.05 g/kg. A pronounced shift in the grade distribution was observed over the decade. The area classified as 0.75 - 1.00 g/kg contracted substantially from 60.08% to 34.62% of total cultivated land. Concurrently, the proportions of the 1.00 - 1.25 g/kg and > 1.25 g/kg grades expanded from 31.67% to 52.30% and from 2.46% to 10.07%, respectively (Figure 2). The net change in TN from 2005 - 2009 to 2015 - 2019 indicated a general trend of accumulation with localized decreases observed in specific areas (Figure 3a). Across the entire study area, TN increased by an average of 0.09 g/kg, representing a 9.38% rise relative to 2005 - 2009 baseline. Areas exhibiting a decrease accounted for 19.48% of the total cultivated area with the majority of these (17.81% of total area) showing

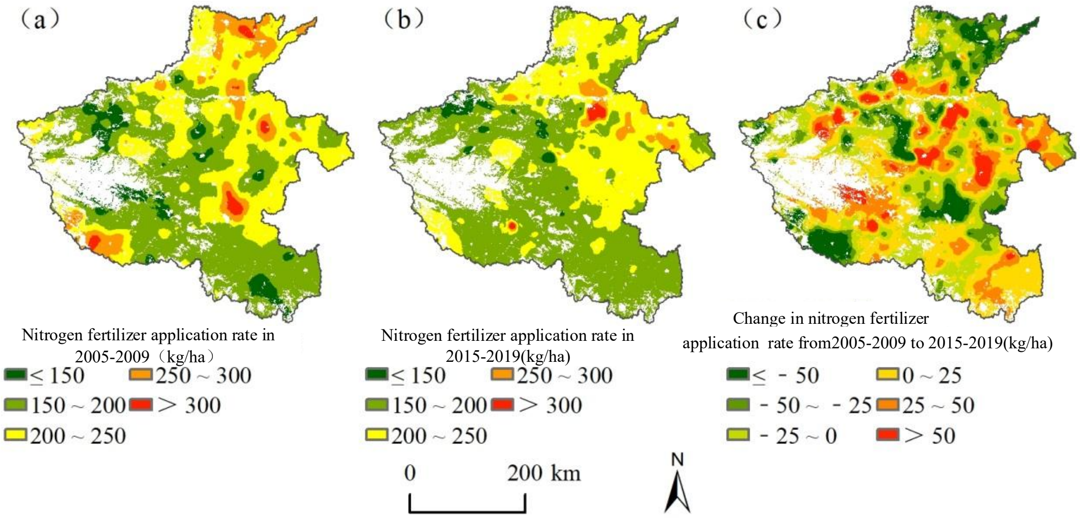

Figure 4. Spatial distribution of nitrogen application rate in 2005 – 2009 (**a**), 2015 -2019 (**b**), and its changes (**c**).

reductions within the range of -0.20 to 0.00 g/kg. In contrast, among areas where TN increased, the dominant change intervals were 0.00 - 0.20 g/kg and 0.20 - 0.40 g/kg, encompassing 57.23% and 21.41% of the total cultivated area, respectively (Figure 3b). The observed spatiotemporal dynamics of TN reflected the integrated influence of multiple environmental and anthropogenic drivers including climate, parent material, and long-term fertilization practices [21]. Since the 1980s, the progressive increase in TN across cultivated soils in this region has been predominantly attributed to agronomic management interventions, particularly increased nitrogen application rates, widespread adoption of straw return, and organic matter improvement strategies, operating against the background of inherent topographic and pedological variability [22]. Collectively, these findings revealed a cultivated land system characterized by a stable spatial pattern of TN with modest yet significant temporal accumulation. This behavior was consistent with a steady-state agroecosystem regulated by the integrated forcing of climate, landform, parent material, and increasingly convergent agronomic management practices.

Spatiotemporal evolution of nitrogen application rationality

(1) Changes in actual nitrogen application rate

Cross-validation of the interpolation results demonstrated satisfactory predictive performance. The Pearson correlation coefficients between the interpolated values and the measured nitrogen application rates were 0.61 ($P < 0.01$) for 2005 - 2009 period and 0.68 ($P < 0.01$) for 2015 - 2019 period, indicating that the interpolated surfaces reliably captured the spatial variation patterns of nitrogen application. The spatial distribution and statistical summary of winter wheat nitrogen application rates revealed a persistent spatial pattern across both study periods, characterized by higher application rates in the northern and eastern regions and lower rates in the southern and western parts of the study area. Nitrogen application rates were predominantly concentrated within 150 - 200 kg/ha and 200 - 250 kg/ha. The mean application rate exhibited a slight decline over the decade from 201 kg/ha in 2005 - 2009 to 198 kg/ha in 2015 – 2019 (Figure 4). Spatial changes in nitrogen application between the two periods showed that areas of decreased application were primarily located in the northern and southwestern portions of the study area, while other regions displayed mixed patterns of both increases and decreases. Overall, areas experiencing a reduction in nitrogen application accounted for 51.43% of the

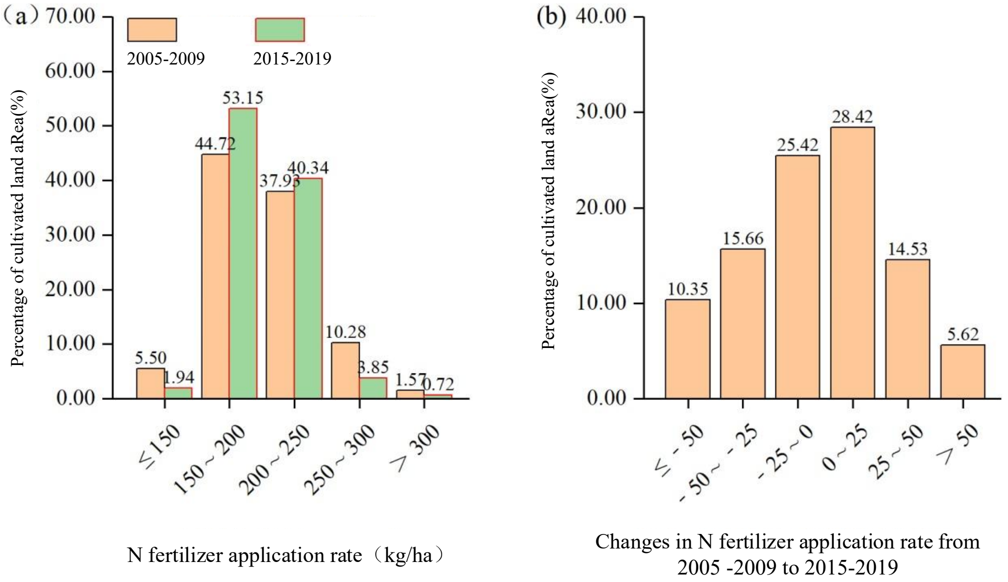

Figure 5. Area percentage of different nitrogen application rates (**a**) and the changes of nitrogen application rates (**b**).

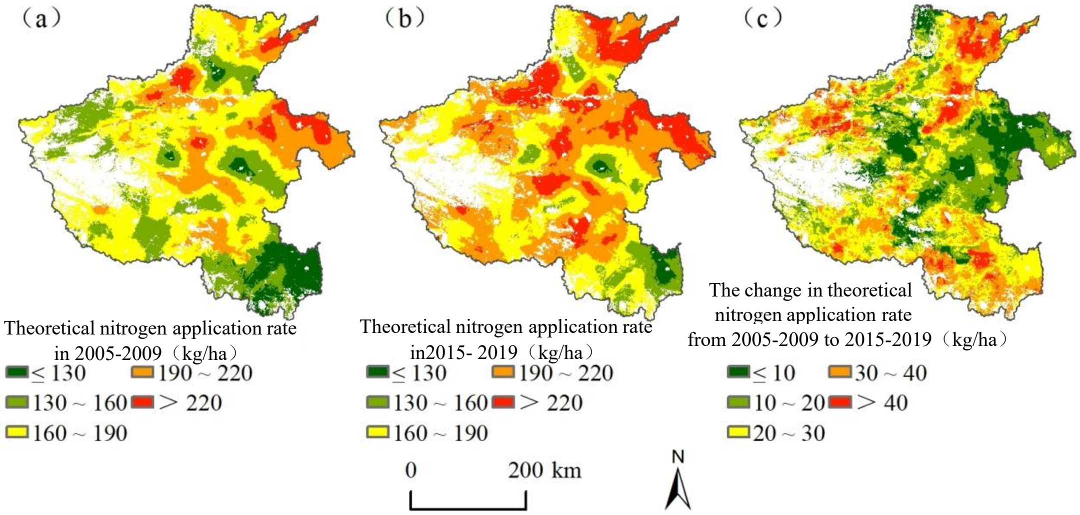

Figure 6. Spatial distribution of theoretical nitrogen application rate in 2005 – 2009 (**a**), 2015 – 2019 (**b**), and its change value (**c**).

total cultivated land, compared to 48.57% where application rates increased. Regardless of the direction of change, the magnitude of change was predominantly within the range of 0 - 25 kg/ha, suggesting a trend toward moderate adjustment rather than drastic shifts in fertilization practices (Figure 5).

(2) Changes in theoretical nitrogen application rate

The spatial distribution of theoretical nitrogen application rates for winter wheat was estimated for the two study periods based on crop yield and nitrogen uptake coefficients. The results showed that the spatial patterns for both periods were broadly similar with consistently lower values concentrated in the southeastern portion of the study area (Figure 6). Between the two periods, a marked increase in theoretical nitrogen application rates was observed across the entire

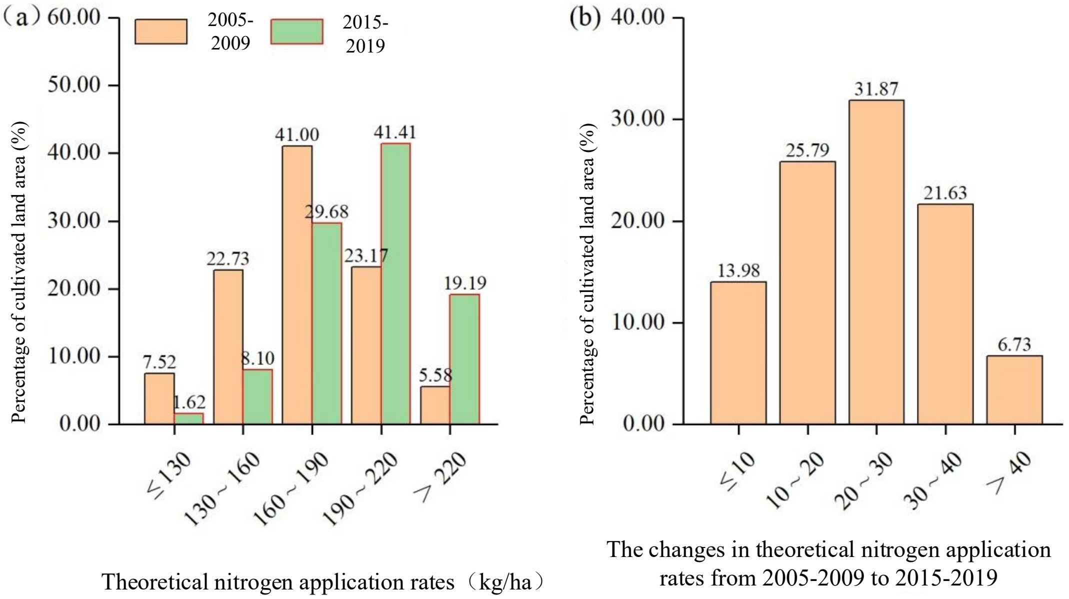

Figure 7. Area percentage of different theoretical nitrogen application rates (**a**) and the changes of theoretical nitrogen application rates (**b**).

study area, which was primarily driven by improvements in cultivated land productivity that resulted in higher crop yields and consequently greater nitrogen removal from the soil through grain harvest. To sustain crop growth and replenish soil nitrogen pools depleted by intensified production, a higher nitrogen supply through fertilization was required. As a result, the mean theoretical nitrogen application rate increased from 172 kg/ha in 2005 - 2009 to 195 kg/ha in 2015 - 2019. The frequency distribution of theoretical application rates shifted accordingly over the decade. During 2005 - 2009 period, the dominant application rate class was 160 - 190 kg/ha, which accounted for 41.00% of the total cultivated area. By 2015 - 2019 period, the modal class had shifted upward to 190 - 220 kg/ha, encompassing 41.41% of the cultivated area, reflecting the general increase in nitrogen demand associated with productivity gains (Figure 7). The magnitude of increase in theoretical nitrogen application rates between the two periods exhibited spatial heterogeneity across the study area. Regions with relatively modest increases were concentrated in the eastern, central, and northwestern parts. The area distribution by increment class was that increments of 20 - 30 kg/ha occupied the largest proportion (31.87% of total cultivated area) followed by 10 - 20 kg/ha (25.79%), 30 - 40 kg/ha (21.63%), ≤ 10 kg/ha (13.98%), and > 40 kg/ha (6.73%). Such graded pattern suggested that while productivity gains were widespread, their magnitude varied systematically across different agroecological zones within the study region.

(3) Temporal evolution of nitrogen application rationality

The rationality of nitrogen application for winter wheat was assessed by comparing actual application rates with theoretical requirements with the spatial distribution and categorical statistics. The spatial patterns of nitrogen application rationality were broadly similar between 2005 - 2009 and 2015 - 2019 with rational fertilization dominating the landscape in both periods (Figure 8). The most prominent irrational practice was excessive application, which was predominantly concentrated in localized areas within the northern, eastern, and southeastern portions of the study area. Quantitative analysis revealed substantial improvements in fertilization practices over the decade. The proportion of cultivated land under rational nitrogen application increased markedly from 51.49% in 2005 - 2009 to 77.38% in 2015 –

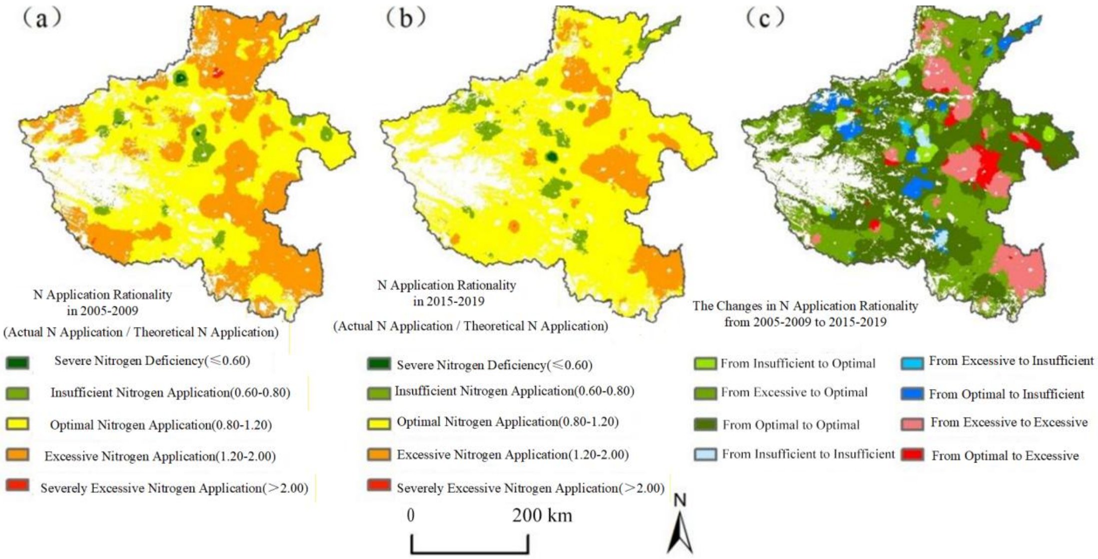

Figure 8. Spatial distribution of nitrogen application rationality in 2005 – 2009 (**a**), 2015 – 2019 (**b**), and its changes (**c**). The notes "Insufficient" in (**c**) included "Severely insufficient" and "Insufficient", while "Excessive" included "Severely excessive" and "Excessive".

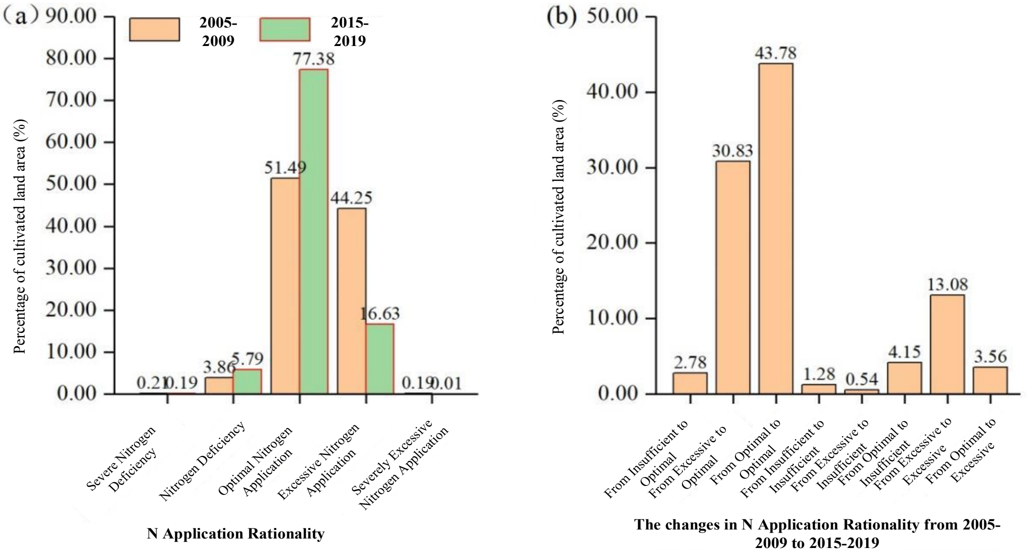

Figure 9. Area percentage of different nitrogen application rationality levels (**a**) and change types (**b**). The notes "Insufficient" in (b) included "Severely insufficient" and "Insufficient", while "Excessive" included "Severely excessive" and "Excessive".

2019. Concurrently, the area affected by excessive application declined sharply from 44.25% to 16.63%, indicating a significant reduction in over-fertilization across the region. Areas with insufficient application remained minimal throughout both periods, accounting for less than 5% of the total cultivated area. The dynamics of nitrogen application rationality between 2005 - 2009 and 2015 - 2019 were characterized by a dominant trend of improvement. The most common transition was the persistence of rational application, which accounted for 43.78% of the total cultivated area. A substantial portion of the landscape, 30.83% of cultivated land, transitioned from (severely) excessive to rational application, while 2.78% shifted from (severely) insufficient to rational application (Figure 9). Collectively, these improvements affected over one-third of the study area, reflecting the effectiveness of ongoing fertilization management adjustments. Despite these positive trends, irrational nitrogen application persisted on 22.61% of cultivated land by 2015 - 2019. This category included areas that remained consistently problematic throughout the study period with 13.08% maintained (severely) excessive status and 1.28% remained (severely) insufficient. Additionally, a small proportion of cultivated land exhibited deterioration in fertilization practices including transitions from rational to (severely) excessive (3.56%) and from rational to (severely) insufficient (4.15%). Notably, 0.54% of the area shifted from (severely) excessive to (severely) insufficient, representing an extreme case of maladaptation where over-fertilization was replaced by under-fertilization without passing through the rational application stage. These findings indicated that, while substantial progress had been made in optimizing nitrogen fertilization across the study area, targeted interventions remained necessary to address persistent irrational practices and prevent the emergence of new imbalances in specific localities.

Spatial optimization of nitrogen fertilizer application and economic benefits

Despite substantial improvements in nitrogen application rationality between 2005 - 2009 and 2015 - 2019 periods, issues of inappropriate fertilization persisted across portions of the study area. To address these challenges while balancing the multiple objectives of cultivated land protection, grain production stability, and environmental sustainability, a spatially explicit optimization of nitrogen application rates was undertaken within the framework of the "crop-farmland-environment" system and implemented by using the theoretical nitrogen application rate as an ideal reference. For cultivated land parcels already classified as having rational fertilization, the optimization value was set to zero, indicating no adjustment required. For all other parcels, map algebra was applied by using the formula of “Optimized application rate = theoretical application rate - actual application rate”. The resulting raster surface provided spatially explicit guidance for fertilization adjustment, in which negative values indicated the magnitude of reduction required, while positive values indicated the magnitude of increase needed, and zero values denoted areas where current practices were already optimal and required no modification (Figure 10).

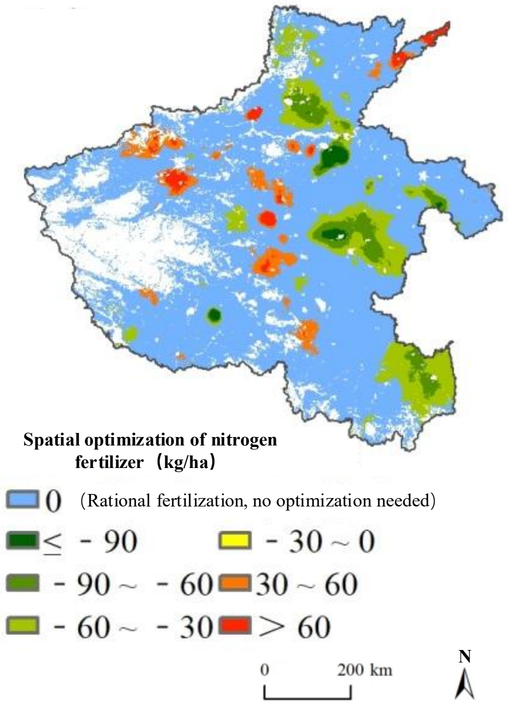

Figure 10. Spatial optimization of the 2015 - 2019 nitrogen application status.

Based on 2015 - 2019 baseline, the spatial optimization analysis revealed that 77.39% of the total cultivated area required no adjustment in nitrogen application, confirming the predominance of rational fertilization practices identified earlier. Among the areas requiring modification, 16.64% of cultivated land needed nitrogen reduction, while 5.98% required increased application (Figure 11). For areas requiring reduction, the adjustment magnitudes were predominantly within the ranges of -60 to -30 kg/ha and -90 to -60 kg/ha, accounting for 10.95% and 4.63% of the total cultivated area, respectively. For areas requiring increase, the adjustment magnitudes were concentrated in the ranges of 30 - 60 kg/ha and > 60 kg/ha, encompassing 4.39% and 1.59% of the total cultivated area, respectively.

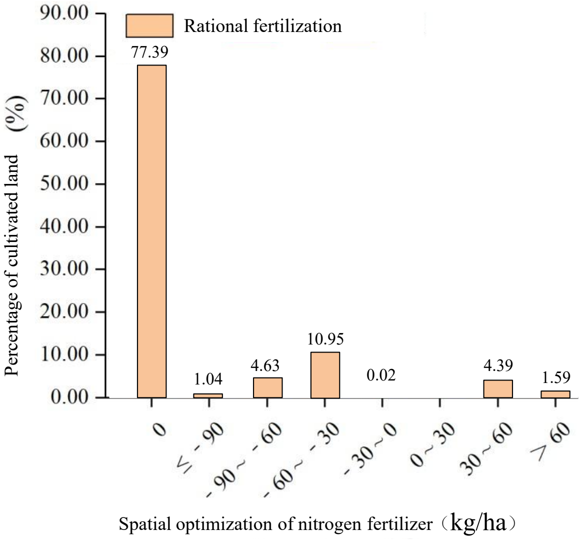

Figure 11. Areal percentage distribution of the 2015 - 2019 nitrogen application.

Extrapolating the optimization recommendations to the regional scale, the study area encompassed approximately 7.5141 × 10^6 ha of cultivated land during the 2015 - 2019 period with the assumption of continuous winter wheat cultivation. Across 22.61% of cultivated land requiring adjustment, the mean recommended nitrogen reduction was -25 kg/ha. The total reduction in nitrogen applications aggregated across all optimization areas was estimated at -4.247 × 10^7 kg. Converting this nitrogen reduction to urea equivalent (assuming a nitrogen content of 46%), the optimization would correspond to a reduction of approximately 9.233 × 10^7 kg of urea fertilizer. Based on the retail price range of urea in Henan, China during 2015 – 2019, which was ¥1.85 - 2.10/kg (CNY) with a median price of ¥2.0/kg, the direct economic benefit from reduced fertilizer expenditure would amount to approximately ¥184.66 million. Beyond these direct economic savings, the reduction in nitrogen application would also contribute to mitigating environmental pollution associated with fertilizer overuse including decreased nitrogen leaching, reduced greenhouse gas emissions, and lower risks of aquatic eutrophication. These ecological co-benefits, while not quantified monetarily in the present study, represented additional significant advantages of the optimized fertilization strategy.

Conclusion

This study developed a systematic framework for diagnosing and optimizing nitrogen application rationality for winter wheat within the "crop-cropland-environment" synergistic system in Henan, China. The spatiotemporal analysis revealed that the cultivated land system was progressively approaching a steady state as evidenced by the increasing trend and stable spatial pattern of TN content over the study period. Nitrogen application rationality improved substantially with rational fertilization becoming predominant by the end of the study period. Nevertheless, a notable proportion of cultivated land continued to exhibit suboptimal fertilization practices, underscoring the need for targeted interventions. The spatially explicit optimization strategy proposed herein offered a viable pathway for reconciling the multiple objectives of cultivated land protection, grain production stability, and environmental sustainability. Implementation of this optimization would yield substantial reductions in nitrogen fertilizer use, translate into direct economic savings, and deliver significant ancillary environmental benefits. These findings provided a scientific basis and practical reference for precision fertilization management and sustainable agricultural development in major grain-producing regions.

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