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Nutrient Balance–Based Assessment of Nitrogen and Phosphorus Bearing Capacity in Shandong Farmlands

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Abstract: Recycling organic nutrient resources is important for reducing dependence on synthetic fertilizers and improving nutrient management in integrated crop–livestock food systems. Using the NUFER model, official statistics, published parameters, and field-survey data, this study quantified the temporal and spatial patterns of nitrogen (N) and phosphorus (P) bearing capacity in the agricultural food system of Shandong Province from 1994 to 2018 and at the county level in Liaocheng City in 2019. In this study, N/P bearing capacity refers exclusively to an operational organic nutrient supply–demand ratio rather than environmental bearing capacity. Results reveal a general downward trend in N/P bearing capacity, accompanied by significant spatial variations. The bearing capacity was positively correlated with livestock density and farming structure, whereas negatively correlated with per capita Gross Domestic Product (GDP) and urbanization rates, and exhibited a quadratic linear relationship with cropping structure. Detailed regional analysis indicates that the N bearing capacity in Dongchangfu District, Linqing City, and Guan County of Liaocheng’s food system fall below 1, indicating that the modeled potentially recyclable organic N supply was lower than the corresponding net crop-product N demand. In the other counties, the modeled organic N supply exceeded this demand on a theoretical mass basis. In Gaotang County, Chiping District, Dong’e County, and Yanggu County, P bearing capacity exceeded 1, reaching 3.16 in Yanggu County, indicating that potentially recyclable organic P exceeded crop-product P removal in quantitative terms. Moran’s I test showed no statistically significant overall spatial autocorrelation among the county-level units.

Keywords: nitrogen; phosphorus; food system; livestock density; spatial variation

1. Introduction

Considering rapid economic and technological advancements, resource scarcity has emerged as a pressing global challenge [1,2]. Nitrogen (N) and phosphorus (P) are known to be essential macronutrients for biological functions and are critical in ensuring food security [3,4]. The N use efficiency of major crops in China stands at approximately 30%, markedly lower than that of the United States (~65%) and of the global average (47%) [5]. Likewise, P fertilizer use efficiency is around 13%, which is lower than Japan (26%), the United Kingdom (22%), and the United States (18%). Such nutrient utilization inefficiency results in considerable losses, triggering various



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environmental challenges, such as climate change, water body eutrophication, and soil acidification [6,7]. Recent studies further indicate that excessive N losses from agricultural systems also contribute significantly to atmospheric pollution and reactive N accumulation at the global scale [8,9]. Furthermore, the livestock sector significantly contributes to N and P footprints due to inadequate manure management and geographical variations across farming zones [10]. Recent evidence suggests that inefficient manure recycling and spatial mismatch between crop and livestock production remain key drivers of nutrient surpluses in agricultural systems [11]. Therefore, for addressing inefficiencies in N and P use across agriculture, improved management practices in the livestock sector are essential to mitigate environmental impacts and ensure sustainable global food production amid growing resource scarcity [12]. In particular, substituting chemical fertilizers with livestock manure has been widely recognized as an effective strategy to enhance soil quality and maintain crop productivity while reducing environmental risks [13].

China's vast and varied landscape presents distinct challenges in nutrient management due to the geographical disconnection among crop production, livestock farming, and urban consumption. This disconnection can lead to inefficiencies and environmental impacts, such as nutrient imbalances and environmental pollution. The national scale analysis highlights the need for more localized studies to understand how regional practices influence overall nutrient balances and food security. This sets the stage for the development of models like NUFER, which delve into these regional dynamics to provide a better understanding of nutrient cycling and balance. To tackle this challenge, Ma et al. investigated nutrient cycling and balance within food systems, leading to the development of the NUFER (Nutrient Flows in Food Chain, Environment, and Resource Use) model [14]. Recent studies have further emphasized the importance of closing nutrient loops through recycling of livestock manure and human excreta to enhance sustainability in food systems [15]. The NUFER model marks the first in-depth evaluation of N and P flows on both national and regional scales in China, methodically analyzing their dynamics and efficiency across various stages—crop production, livestock breeding, food processing, and household consumption—and their environmental repercussions. Bai et al. expanded this work by developing the NUFER-animal model, offering a nuanced analysis of nutrient use and loss across the diverse animal production systems [10]. They underscored that the critical integration of agriculture and animal husbandry, producing sustainable development and reduced environmental pressures, will have an impact on efficient nutrient recycling. Ma et al. observed that the nutrient balance in food systems was influenced by driving forces, including economic, social, environmental effects, and binding interactions, which can significantly influence the dynamics of nutrient flows, leading to various environmental outcomes [16]. Although previous studies have explored the reduction of fertilizer usage on a national scale, they have rarely examined the geographical disconnections among crop production, livestock farming, and urban areas [17,18]. This gap in research highlights a critical need to understand regional dynamics in agricultural systems, particularly in provinces like Shandong. As a leading agricultural hub and a vital grain-producing region in China, Shandong province presents an ideal case study to explore how local agricultural practices impact national food security strategies [19].

Utilizing official statistics and literature from 1994 to 2018, this study delves into the variations and spatiotemporal distribution of N and P nutrients within Shandong province's food systems [20]. This research aims to identify and analyze the factors influencing the bearing capacity for N and P in food systems. The objectives of the present study are: (a) to assess how variations in culture density and culture structure impact the bearing capacity for N and P in food systems; (b) to evaluate the relationship between per capita gross domestic product and urbanization rate with nutrient management efficiency and fertilizer use; (c) to determine how different planting structures affect the efficiency of N and P use and propose strategies to optimize these structures for better nutrient management. High culture density and intensive culture structures often lead to increased nutrient input requirements and greater potential for nutrient runoff. For example, in the Netherlands, intensive livestock farming has led to significant nutrient management challenges, necessitating advanced technologies and regulations to mitigate environmental impacts. Countries with higher per capita GDP, like Germany, typically have better access to advanced nutrient management technologies and practices [21]. These result in more efficient use of fertilizers and reduced environmental impact compared to lower-income countries, where limited resources can lead to less efficient practices. Rapid urbanization can alter land use patterns, affecting nutrient runoff and management. The adoption of diverse and optimized planting structures can enhance nutrient use efficiency by improving soil health and reducing fertilizer needs. Previous analyses in China have often overlooked the impact of these factors on nutrient management efficiency. As a result, the effects of varying culture densities, culture structures, and urbanization on fertilizer use and nutrient management have not been fully explored. This research aims to fill this gap by evaluating how these factors specifically influence nutrient management in China and by proposing targeted measures to improve efficiency and reduce fertilizer use [22]. In 2019, data were collected by conducting interviews with key livestock farms in Liaocheng City, Shandong province. This research focuses on examining the factors influencing

the bearing capacity for N and P. By analyzing the feasibility of substituting chemical fertilizers with livestock manure, considering the disparities in crops and livestock production distribution, the study aims to provide insights into sustainable agricultural development. The findings from Liaocheng City provide a valuable regional case study, offering practical insights for optimizing resource utilization and promoting sustainable agricultural management in Shandong Province and other areas with similar agricultural and environmental conditions.

2. Materials and Methods

2.1. Data Sources

This study chooses Shandong Province as the research object at the regional scale. Shandong Province, located in China's eastern coastal region, has 7.515 million hectares of arable land, but the per capita arable land is only 0.08 hectares, or 1.2 mu. Shandong Province has high grain output and a well-developed livestock and poultry production sector, which also carries a huge N and P nutrient problem in the face of mass production of animal and plant products. In addition, Liaocheng City, a representative city in Shandong Province, is selected for county-level research. Liaocheng City is in the west of Shandong Province, with jurisdiction over Dongchangfu District, Linqing City, Chiping District, Dong'e County, Guan County, Gaotang County, Yanggu County, and Shen County. The terrain is the Yellow River impact plain, which belongs to the temperate monsoon climate. The planting and livestock industry are the primary industries of Liaocheng City.

To mitigate the impact of the COVID pandemic period from 2019 to 2023 on research data, this study took the data up to 2018, selecting Shandong province as a regional-level case study (Figure S1). This includes statistical outcomes of major livestock inventory and off-take in Shandong province from 1994 to 2018 (Figure S2). The data used in this study were primarily obtained from statistical records, a literature review, and field surveys. Statistical data were collected from the Shandong Statistical Yearbook and the statistical yearbooks of relevant prefecture-level cities for the period 1995–2019. These data included the permanent rural and urban populations of cities and counties across Shandong Province, including county-level population data for Liaocheng City in 2019, as well as per capita grain consumption, cultivated land area, and crop production. Parameters obtained from the literature review mainly included the N and P contents of crop products and crop straws, straw-to-yield ratios, straw return-to-field ratios, and other crop-related parameters. Livestock and poultry parameters included N and P excretion rates, manure return-to-field and direct discharge ratios, as well as NH_3 volatilization, N_2O emission, and denitrification ratios in animal pens. In addition, data on the N and P contents of food consumed by households and the food consumption patterns of rural and urban residents, including the proportions of meals consumed at and away from home, were compiled. Detailed parameter values are provided in Tables S1–S8 of the Supplementary Material [23–25]. Field survey data were obtained through a survey conducted with the Shandong Provincial Animal Husbandry Station in 2019. The survey collected information on large-scale livestock and poultry farms in the counties and districts of Liaocheng City, Shandong Province. The dataset included the annual numbers of animals slaughtered or sold, livestock inventories, and the types of animals raised (Figure S3).

2.2. NUFER Model

The research system of the NUFER model can be set according to the research needs, and the input and output items also change with different research systems, which can be divided into crop production subsystem, livestock production subsystem, food processing subsystem, and household consumption subsystem, which is defined as the food chain system or food nutrient pyramid. Based on the NUFER modeling approach [14], this study defines the system boundary as including crop production, livestock and poultry production, household consumption, and the recycling of crop straw, animal manure, and human excreta. Following the principle of mass balance, the model quantifies N and P inputs, outputs, recycling flows, and losses within the linked crop–livestock–food chain [26]. Based on the material balance cycle and material balance theory, the input and output items of N, P, and other elements in the region can be quantitatively calculated. To avoid confusion with the broader concept of environmental bearing capacity, this study defines the N/P bearing capacity of the food system as an operational organic nutrient supply–demand ratio. In the remainder of this paper, the terms “N bearing capacity” and “P bearing capacity” refer exclusively to the corresponding organic nutrient supply–demand ratios defined below, rather than to soil nutrient status, agronomic nutrient sufficiency, or environmental bearing capacity. The ratio compares the amount of potentially recyclable organic N or P supplied by crop straw, livestock and poultry manure, and human excreta with the corresponding net crop-product nutrient demand estimated by the model. For N, the net crop-product N demand is defined as the N contained in primary crop products after deducting the contributions of biological N fixation and atmospheric N deposition. For P, because the model does not include corresponding P-input adjustments, the net crop-product P demand is represented by the P contained in primary crop products.

This indicator evaluates whether organic nutrient resources within the food system are theoretically sufficient to offset crop nutrient removal. This definition is based on a nutrient-resource linkage framework that connects crops, livestock, and food throughout the entire food production and consumption process [14]. Among them, organic nutrient N includes the content of N (P) in crop stalks (such as corn stalks, straw, etc.), the content of N (P) in livestock and poultry feces and urine, and the content of N (P) in human urine as an additional source of N. The N content of crop main products refers to the N content measured from the main products of crops (such as grains, beans), which is used to measure the amount of N absorbed by crops. In this paper, the N/P bearing capacity of food systems in Shandong province during 1994–2018 was calculated, and the historical changes and spatial variations of N and P losses in the system were also calculated. The N/P bearing capacity of the food system and returned nutrients of Liaocheng district and county in 2019 were calculated. The research covered all aspects of food production and consumption, encompassing crops (Equations (S1)–(S11)) [14,23,24,27–29], livestock (Equations (S12)–(S21)) [10,14,28–31], and food (Equations S22–S29) [14,28,29,32,33], as illustrated in Supplementary Materials. Furthermore, the 2019 N/P bearing capacity of the food system, including its return to the field in districts and counties of Liaocheng City, was computed using Equations (S30)–(S33).

2.3. Scenario Analysis

In this study, the NUFER model was used to simulate ammonia flow in farmland and livestock production subsystem at the regional scale, and to evaluate N (P) utilization efficiency and N (P) environmental emission. Such scenario-based approaches have been widely applied to assess the potential of improving N use efficiency and reducing emissions in integrated crop–livestock systems [34]. The effects of improved nutrient management measures on the reduction of N (P) emissions and the improvement of N (P) production efficiency under different scenarios were analyzed. Drawing on historical data, this study delineated three distinct N (P) management scenarios [14]:

Scenario 1 (S1): Synthetic fertilizer demand was adjusted to balance crop N (P) demand after accounting for nutrient return from crop straw under improved soil management. Actual crop production, planting structure, and other coefficients were held at the observed values for each year (Equations (1) and (2)).

$$FN, S1 = (SN + GN) \times NUF - SMN \quad (1)$$

$$FP, S1 = (SP + GP) \times PUF \quad (2)$$

Scenario 2 (S2): S1 plus enhanced recycling of livestock and poultry manure. Manure N (P) was allowed to substitute for synthetic fertilizer only after applying manure collection, treatment, return-to-field, and nutrient-availability coefficients. This scenario assumes that manure can be returned within the modeled region, but it does not imply that all farms have equal transport feasibility (Equations (3) and (4)).

$$FN, S2 = FN, S1 - (ADN + BFN + RSN \times AFN + NRN) \quad (3)$$

$$FP, S2 = FP, S1 - (RSP \times AFP + NRP) \quad (4)$$

Scenario 3 (S3): S2 plus additional recovery of nutrients from human excreta after treatment. Human excreta were included as an additional organic nutrient source, but their contribution was expected to be small relative to straw and livestock manure (Equations (5) and (6)).

$$FN, S3 = FN, S2 - HRN \times AFN \quad (5)$$

$$FP, S3 = FP, S2 - HRP \times AFP \quad (6)$$

Here, F represents the theoretical demand for compound fertilizer. SN and GN represent the N contents of crop straw and grain, respectively. NUF denotes the N uptake factor, while SMN, ADN, and BFN represent the amounts of N supplied through soil mineralization, atmospheric deposition, and biological N fixation, respectively. RSN represents the N content of straw returned to the field, and AF denotes the availability factor. NRN refers to the N content of livestock and poultry manure and urine returned to the field, whereas HRN represents the N content of human excreta returned to the field. Similarly, SP and GP represent the P contents of crop straw and grain, respectively. PUF denotes the P uptake factor. RSP represents the P content of straw returned to the field, NRP refers to the P content of livestock and poultry manure and urine returned to the field, and HRP represents the P content of human excreta returned to the field. The AF of N, NUF and PUF of different plants can be obtained from the Supplementary Material. The AF of P is set at 1.0 [35]. The value of 1.0 represents a simplifying long-term potential availability assumption.

2.4. Heatmap Analysis

Employing ArcMap 10.2, a heatmap analysis was performed to map the distribution of livestock and poultry farms in Liaocheng City, Shandong province, alongside their N and P emission levels. Within these heat maps, darker hues signify areas of heightened N and P nutrient emissions stemming from livestock and poultry manure.

2.5. Data Analysis

This research investigated the spatial distribution patterns of N/P and their return-to-field bearing capacity within Liaocheng City, Shandong province's food system, aiming to determine the presence of clustering phenomena among these elements. Spatial autocorrelation analysis was conducted employing ArcMap 10.2 (Esri, Redlands, CA, USA) and GeoDa software (Center for Spatial Data Science, University of Chicago, Chicago, IL, USA). Statistical data processing was carried out in Excel (Microsoft Corporation, Redmond, WA, USA) and Matlab (MathWorks, Natick, MA, USA), with linear interpolation employed to address missing data. Data integration and visualization were performed using Origin (OriginLab Corporation, Northampton, MA, USA), ArcMap 10.2, and GeoDa.

3. Results and Discussion

3.1. N/P Bearing Capacity

3.1.1. Nutrient Quantities and Returned to the Field

As the nation's economy has rapidly evolved, public demand has correspondingly surged. Between 1994 and 2018, the nutrient content of crops was consistently increased, accompanied by a gradual rise in the nutrient content of straw. In Shandong province, a premier agricultural region, variations in geographical features, crop resources, planting conditions, and agricultural practices contributed to the uneven spatial distribution of agricultural outputs [36]. This disparity extended to regional variations in straw and its nutrient resources, as illustrated in Supplementary Materials, Figure S12.

Concurrently, Shandong province has emerged as a significant hub for livestock and poultry farming. Since 1980, the expansion of the population and changes in dietary habits have led to a notable increase in the consumption of livestock and poultry products, further accelerating the rapid development of China's livestock farming sector [37]. This study examined changes in N and P nutrients in livestock and poultry manure in Shandong province from 1994 to 2018. Between 1994 and 2018, N nutrients in livestock and poultry manure decreased by 11%, from 1720 to 1527 kilotons, and P nutrients declined by 16%, from 560 to 469 kilotons (Figure S12). The research showed that approximately 67% of the N and 69% of the P in livestock and poultry manure are applied to the soil, while direct discharges account for 61 and 59% of N and P losses, respectively. This suggested a substantial potential for manure nutrients to replace chemical fertilizers [38]. Recent studies have also confirmed that manure application can significantly improve soil nutrient availability and enhance P use efficiency, further supporting its substitution potential [39,40]. Further analysis indicated that trends towards the intensification and scaling of livestock farming are emerging, with manure nutrient distribution showing distinct regional geographical characteristics. Temporal and spatial analyses revealed that livestock farming is increasingly concentrated in the central and southern parts of Shandong province, especially in the cities of Weifang, Liaocheng, Jining, and Heze (Figure S13). These areas possess not only the greatest potential for substituting chemical fertilizers with livestock and poultry manure but also are closely related to the local geographical conditions and policy adjustments. This results in variations in the quantity and structure of livestock farming across regions, leading to an uneven distribution of manure nutrients. Additionally, these regions are focal points for pollution control efforts aimed at reducing nutrient resource wastage and environmental pollution caused by direct discharges [41].

Within the food system examined in this study, human excreta contain relatively fewer nutrients, accounting for a significantly smaller proportion than straw and livestock manure (Figure S12). Although the nutrient content in human excreta may be considered negligible, focusing on its management practices remains crucial. This approach not only reduces the adverse impacts of indiscriminate discharge but also facilitates the rational utilization of nutrients from human and animal manure, promoting their conversion into fertilizers, feed, and energy.

3.1.2. Temporal and Spatial Variations of N/P Bearing Capacity

The N/P bearing capacity used in this study represents the relationship between potentially recyclable organic nutrients within the food system and the modeled nutrient demand of primary crop products. When the N/P bearing capacity of the food system is equal to 1, the theoretical supply of organic nutrients is equivalent to the nutrient

demand of crop products. A value below 1 indicates that the modeled potential organic nutrient supply is lower than the corresponding crop product nutrient demand. Conversely, a value above 1 indicates that the modeled potential organic nutrient supply exceeds this demand. However, the indicator does not fully account for soil nutrient stocks, nutrient availability to crops, transport constraints, seasonal synchronization, field-level application efficiency, or environmental loss pathways. Therefore, these results should be used to identify potential nutrient surplus or shortage risks rather than to directly determine field-scale fertilizer replacement rates.

The N/P bearing capacity of the food system is determined by the ratio of organic nutrients to the primary crop products. This study focuses on organic nutrients, including N and P contents in straw, livestock and poultry manure, and human excreta. The research showed that N and P nutrients were most concentrated in livestock and poultry manure, followed by straw, while the nutrient content in human excreta was relatively low and nearly negligible. From 1994 to 2018, the N return rate from livestock nutrients increased initially from 33% in 1994 to 34% in 1999, while it gradually decreased to 30% in 2018, experiencing minor fluctuations throughout this period (Figure S12). In contrast, the P return rate consistently declined, a trend primarily attributable to changes in N fertilizer use in Shandong province, which increased from 1995 kilotons in 1994 to 2599 kilotons before decreasing to 2013 kilotons, accompanied by an increase in P fertilizer used from 780 to 1228 kilotons (Figure S12). The widespread adoption of chemical fertilizers has resulted in their dominance in agricultural fertilization practices [42]. Furthermore, the scarcity of agricultural labor, the development of livestock farming, and the separation of crops and livestock farming contributed to this trend. Following 1999, the N return amount began to increase, primarily because of policy adjustments, advances in fertilizer technology, and techniques for the harmless reduction of livestock waste. Conversely, the P returns amount remains low, with annual increases in P fertilizer application, mainly due to the difficulty and higher costs of P recovery technology compared to P mining [43,44]. Therefore, the adoption of location-specific management models and treatment methods can effectively reduce environmental pollution and nutrient loss resulting from traditional return-to-field practices. This is particularly important as fertilization strategies strongly influence soil N cycling processes, microbial activity, and associated emissions [45].

From a regional perspective, the cities of Heze, Liaocheng, Dezhou, Binzhou, Jinan, and Qingdao in Shandong province serve as the primary areas bearing the N and P nutrients in the food system (Figure S10–S13). These areas are significant not only as the main production regions for wheat and corn, which are key staple crops and major sources for swine feed, but also as focal points for the concentration of straw, livestock, and poultry manure nutrient resources. Consequently, the capacity for N/P return to the field in these areas was high, and closely linked to local geographical conditions and climate changes [46]. However, spatial variability and uncertainty in N application and management remain critical challenges affecting regional nutrient balances [47]. By employing effective recycling and utilization methods, the potential to substitute chemical fertilizers with waste resources could be significantly enhanced.

3.1.3. Associations between N/P Bearing Capacity and Socioeconomic and Agricultural Variables

In the food system, N and P from livestock and poultry manure are major components of the N/P bearing capacity. Livestock and poultry production varies across different resource endowments, economic conditions, environmental settings, and technological contexts. Particularly notable patterns are observed in relation to economic and geographical characteristics, urbanization levels, and land-resource conditions (Figure S14) [48]. This study examined the associations between per capita GDP, urbanization rate, cropping structure, livestock density, livestock production structure, and the N/P bearing capacity. From 1994 to 2018, the N/P bearing capacity of Shandong Province's food system showed synchronous changes with socioeconomic development, urbanization, and agricultural structural adjustment (Figure 1). As per capita GDP increased, the N/P bearing capacity generally declined. When per capita GDP reached 76,267 yuan, the N/P bearing capacity was 2.17 and 1.67, respectively. A similar decreasing trend was observed with increasing urbanization rate [36]. Changes in planting structure also affected fluctuations in N/P bearing capacity. When the yield ratio of cash crops to grain crops ranged from 45% to 55%, the N/P bearing capacity remained at a relatively low level. In contrast, periods with higher livestock breeding density generally corresponded to higher N/P bearing capacity [49]. For example, the N bearing capacity and P bearing capacity were 4.66 and 3.36 in 1996, respectively, compared with 3.66 and 2.76 in 2005. The breeding structure ratio was highest in 1996, reaching 41%, with corresponding N bearing capacity and P bearing capacity of 4.66 and 3.36, respectively; by contrast, the lowest ratio was observed in 2018, at 13%. These changes reflect the dynamic adjustment between organic nutrient supply and crop nutrient demand.

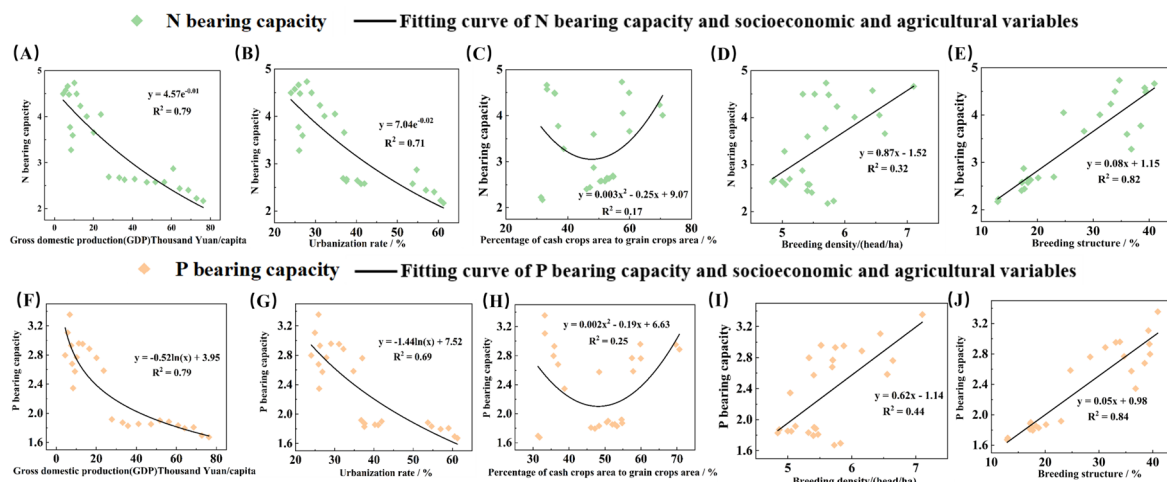


Figure 1. Descriptive associations between socioeconomic and agricultural variables and the organic nutrient supply-demand ratios in the food system of Shandong Province from 1994 to 2018. (A–E) show the relationships of the N bearing capacity with per capita. (A) GDP ($p < 0.001$), (B) urbanization rate ($p < 0.001$), (C) planting structure ($p > 0.05$), (D) breeding density ($p < 0.05$), and (E) breeding structure ($p < 0.001$). (F–J) show the relationships of the P bearing capacity with per capita. (F) GDP ($p < 0.001$), (G) urbanization rate ($p < 0.001$), (H) planting structure ($p < 0.05$), (I) breeding density ($p < 0.001$), and (J) breeding structure ($p < 0.001$). Each panel contains 25 annual observations ($n = 25$), and the confidence interval is 95%.

3.1.4. Scenario Analysis

This study, drawing on data spanning from 1994 to 2018, employed the NUFER model calculation method to establish three distinct N (P) management scenarios, i.e., Scenario 1 (S1), Scenario 2 (S2), and Scenario 3 (S3). It examines the N/P bearing capacity of the food system across these scenarios, including their historical changes and spatial differences, and accounts for the nutrient content of the food system and its return-to-field N/P bearing capacity.

According to Scenario 1 calculations, N and P inputs from chemical fertilizers were based on baseline values of the respective years, coupled with improved soil management practices. As illustrated in Figure 2, an analysis of data from 1995, 2000, and 2005 showed N fertilizer inputs of 2205, 2419, and 2483 kilotons, respectively. In these years, adhering to Scenario 1's N fertilizer strategy, applications could be reduced by 7, 18, and 7%, respectively, significantly decreasing N loss. Between 2010 and 2018, N fertilizer inputs were 2348, 2257, and 2013 kilotons, respectively, compared to the strategic application amounts of 2748, 2603, and 2669 kilotons. This suggests that the N fertilizer applications did not fully satisfy the growth requirements of crop plants. In contrast, P fertilizer applications from 1995 to 2018 were significantly higher than the strategic application amounts outlined in the scenarios (Figure 2). Compared to the applied amounts in the same years, strategic P fertilizer applications were reduced by approximately 63%, potentially resulting in a significant P loss and a likely negative environmental impact. From a regional perspective, strategic fertilizer application amounts at both provincial and municipal levels were similar, particularly in 2000, 2015, and 2018, showing virtually no difference.

Based on Scenario 2 calculations, improved management of livestock and poultry manure reduced the inputs of N and P from chemical fertilizers compared to Scenario 1. At the province level, from 1995 to 2018, N fertilizer inputs decreased by 72, 62, 64, 46, 50, and 47% compared to Scenario 1, without the need for additional P fertilizer. However, the analysis of the municipal level of Scenarios 1 and 2 revealed that during the same period, N fertilizer inputs decreased by approximately 57%, and P inputs by approximately 96%. Additionally, the study indicated that spatial heterogeneity in the distribution of crop cultivation and livestock production in Shandong province has a limited impact on manure utilization for return-to-field practices.

Scenario 3 calculations indicated further improvements in N and P inputs from chemical fertilizers over Scenario 2, achieved by maximizing the use of human excreta in return-to-field applications through enhanced management. However, the strategic application amounts of N and P fertilizers show almost no difference between Scenario 3 and Scenario 2. This suggests that the proportion of human excreta in the food system was relatively small, and thus, it plays a minor role in reducing chemical fertilizer use.

Comparison of the three scenarios revealed that Scenario 2 significantly reduced fertilizer application compared to Scenario 1. In the food system, utilizing livestock and poultry manure for return-to-field significantly reduces chemical fertilizer usage. Fertilizer application rates in Scenarios 2 and 3 were essentially identical,

suggesting that the contribution of N and P from human excreta during return-to-field is minimal and negligible in the food system.

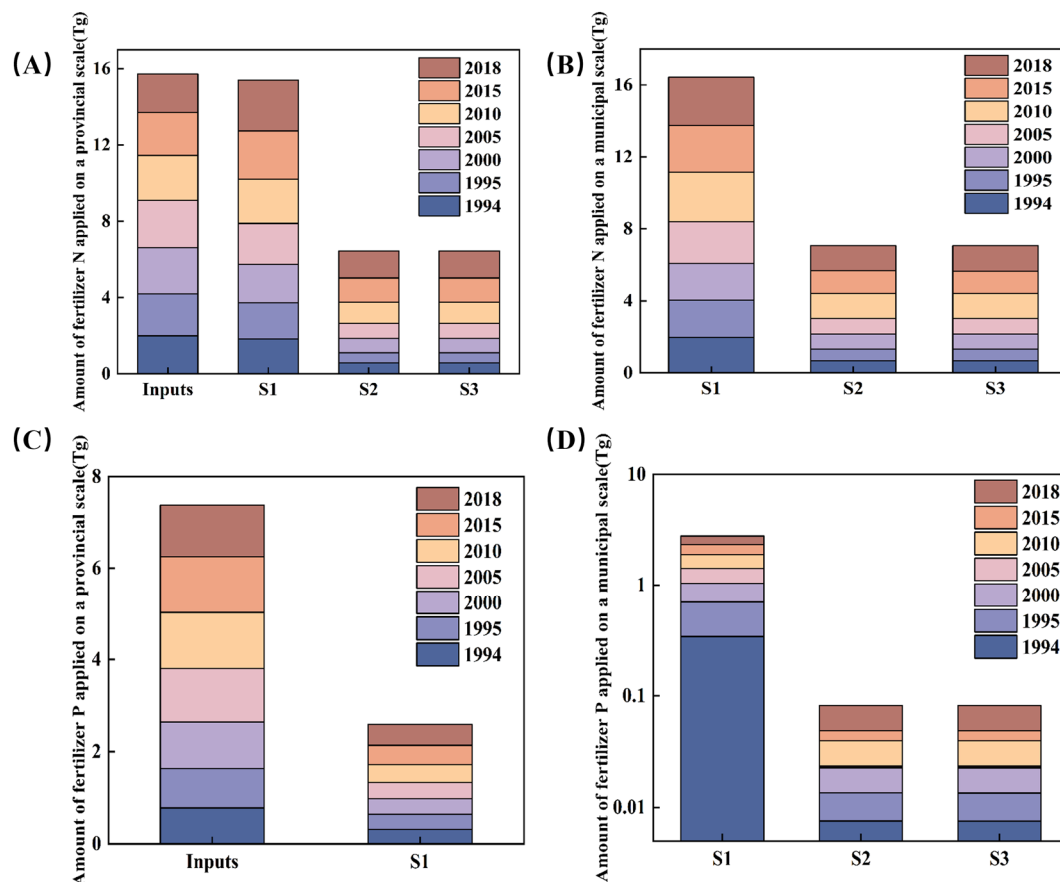


Figure 2. Inputs of synthetic N fertilizer, P fertilizer to Shandong agriculture from 1994–2018, the required inputs of synthetic N for various strategies on a provincial scale (A) and municipal scale (B), and the required inputs of synthetic P for various strategies on a provincial scale (C) and municipal scale (D). Inputs represent the actual input amount, while S1, S2, and S3 represent the theoretical input amount.

3.2. N/P Bearing Capacity in Breeding Intensive Area

3.2.1. Nutrient Resources of the Food System in Liaocheng, Shandong

This study implements data from 1023 scaled farming operations in Liaocheng, Shandong province (Figure S15). The distribution of farm types is as follows: pig farms 21%, cattle farms 2%, poultry farms (including chickens and ducks) 59%, sheep farms 16%, and rabbit farms 2%. At the county level, livestock and poultry farms were mainly distributed in Guan County (20%), Chiping District (19%), Dong'e County (16%), Gaotang County (13%), and Yanggu County (9%). Therefore, in terms of the proportion of farm numbers, livestock and poultry farms were more concentrated in Guan County and Chiping District.

Analysis of nutrient resources in the food system (Figure S16) revealed that N and P fertilizer usage in Liaocheng City in 2019 were 172 kilotons and 92 kilotons, respectively, which is 10% lower than those of 2018. In agriculture, crop nutrient content for N and P was 141 kilotons and 34 kilotons, respectively, with straw adding 52 kilotons of N and 8 kilotons of P, approximately 25% of which was returned to the field. Using the NUFER model and statistical data of livestock and poultry production in Liaocheng City, the N and P emissions from livestock and poultry manure in 2019 were calculated as 82 kilotons and 30 kilotons, respectively, with only 25% and 36% of N and P being utilized for return-to-field. [14,50]. Additionally, emissions of N and P from human excreta were 30 and 7 tons, respectively. Although human excreta contain recyclable nutrients, including nitrogen and phosphorus, their contribution to regional nutrient flows is generally limited compared with agricultural nutrient inputs [51].

3.2.2. N/P Bearing Capacity at Different Regions in Liaocheng, Shandong

The comprehensive assessment of Liaocheng's food system's N bearing capacity (Figure S17) focused specifically on the relationship between N supply and crop demand. The county-level results showed clear spatial variations in the organic nutrient supply–demand ratios across Liaocheng in 2019. The N bearing capacity in Dongchangfu District, Linqing City, and Guan County was below 1, whereas those in the other five county-level units were above 1, with relatively high values observed in Gaotang County and Yanggu County (Figures S17 and S18). In contrast, the N return-to-field bearing capacity was below 1 in all eight county-level units, with Gaotang County showing the lowest value. The difference between N bearing capacity and N return-to-field bearing capacity indicates that only part of the potentially recyclable organic N was returned to cropland under the modeled conditions. The P bearing capacity in Dongchangfu District, Shen County, Linqing City, and Guan County was below 1, whereas those in the other four county-level units were above 1 (Figure S19). Yanggu County had the highest P bearing capacity, reaching 3.16. This relatively high value corresponded to its large poultry and swine populations and the associated manure P generation. Yanggu County also had the highest P return-to-field bearing capacity, reaching 1.06, whereas the values in the other seven county-level units ranged from 0.12 to 0.46. The one-at-a-time sensitivity analysis based on the mean annual model outputs for Shandong Province from 1994 to 2018, showed that the N-related bearing capacity was mainly responsive to atmospheric N deposition and crop-product N content. The P-related bearing capacity was primarily responsive to crop-product P content, livestock P excretion, and the manure return-to-field ratio (Figures S4–S7).

This study's comprehensive analysis of N/P bearing capacity in Liaocheng's food system reveals that emissions from livestock and poultry farming significantly impact these capacities. Furthermore, using heat map technology, we analyzed N and P emissions from livestock and poultry farming across various administrative districts (Figure S20). The results showed that Yanggu County, Shen County, and Dong'e County are significant hotspots with persistently high N and P emissions from livestock and poultry farming. In contrast, Gaotang County, Chiping District, and Dongchangfu District have relatively lower emissions. The heat map's color intensity visually indicated emission levels, reflecting the N/P bearing capacity's strengths and weaknesses in these regions' food systems. This finding laid a crucial foundation for optimizing regional livestock and poultry farming management strategies and enhancing the N and P nutrient cycle.

3.2.3. Spatial Autocorrelation Analysis of N/P and Their Return-to-Field Bearing Capacity in Food System Based on GIS

Moran's I analysis was conducted to examine the overall spatial autocorrelation of the N/P and their return-to-field bearing capacity across the eight county-level units of Liaocheng. The initial step using GeoDa software (Center for Spatial Data Science, University of Chicago, Chicago, IL, USA) involved analysis for local spatial autocorrelation, yielding a Moran's I scatter plot. A hypothesis test for Moran's I coefficient was conducted using the Monte Carlo simulation method with 999 iterations, where a higher value indicated greater stability. For the N bearing capacity, the permutation test yielded a Z-score of 0.8754 and a P-value of 0.2160, indicating no statistically significant global spatial autocorrelation. The N return-to-field bearing capacity also showed no significant global spatial autocorrelation ($Z = 1.0835$, $p = 0.1740$) (Figure 3) [52]. The Moran scatterplot for the N bearing capacity placed Chiping District, Dong'e County, and Gaotang County in the high–high quadrant; Dongchangfu District and Shen County in the low–high quadrant; Guan County and Linqing City in the low–low quadrant; and Yanggu County in the high–low quadrant. These quadrants describe the relative values of each county-level unit and its neighboring units. Further analysis of spatial relationships between administrative districts can be conducted using LISA values [53,54]. At a significance level of 0.01, Shen County was identified as a “low-high” type, indicating it had a low N bearing capacity but was surrounded by regions with high capacity. For the N return-to-field bearing capacity, the figure's first quadrant shows Shen County; the second includes Dongchangfu District and Chiping District; the third features Guan County and Linqing City; and the fourth encompasses Yanggu County, Dong'e County, and Gaotang County. Further examination of spatial relationships using LISA values revealed that none of the eight administrative districts under Liaocheng City reached the local significance threshold.

A local spatial autocorrelation analysis of P bearing capacity within the regional food system was conducted using GeoDa software (Figure 4). The analysis indicated local spatial autocorrelation; however, with a Z-score of -0.4469 and a p -value of 0.3550, the autocorrelation was not significant. The Moran's I scatter plot showed Dong'e County and Gaotang County in the first quadrant; Dongchangfu District and Shen County in the second; Guan County and Linqing City in the third; and Chiping District and Yanggu County in the fourth. Further examination of spatial relationships between administrative districts was conducted using LISA values. The results identified

Guan County as a “low-low” type, surrounded by areas with low P bearing capacity, while Dongchangfu District and Shen County were “low-high” types, surrounded by areas with high capacity. Based on the data from livestock and poultry farms, the relatively low P bearing capacity in these counties may be attributed to the relatively limited contribution of poultry farms, and poultry farms are an important source of P emissions from manure [55]. GeoDa software was used for a local spatial autocorrelation analysis of P return-to-field bearing capacity within the regional food system (Figure 4). The local spatial autocorrelation test yielded a Moran’s I value of -0.1915 , a Z-score of -0.1763 , and a p -value of 0.4690 , indicating an absence of significant autocorrelation. Results indicated Dong’e County and Gaotang County were in the first quadrant. Dongchangfu District and Shen County were in the second. Guan County and Linqing City were in the third. and Dong’e district and Yanggu County were in the fourth. Further analysis with LISA values, at a significance level of 0.01 , showed Shen County as a “low-high” type of local correlation. This suggested that Shen County had a low P return-to-field bearing capacity and is surrounded by areas with higher capacity.

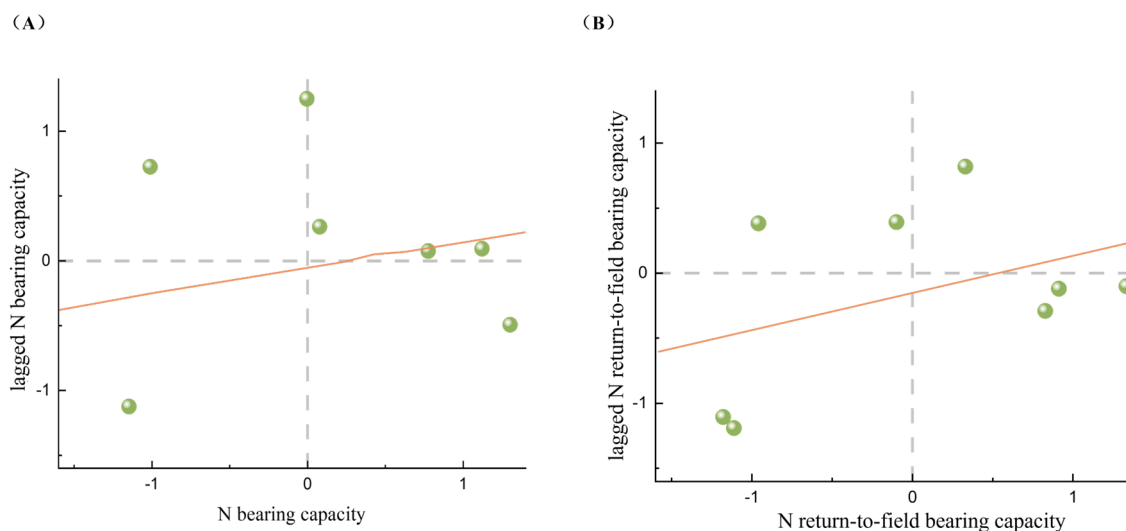


Figure 3. Moran scatterplots for the N bearing capacity (A) and the N return-to-field bearing capacity (B) across eight county-level units in Liaocheng City. The green dots in the picture represent the administrative divisions of Liaocheng City.

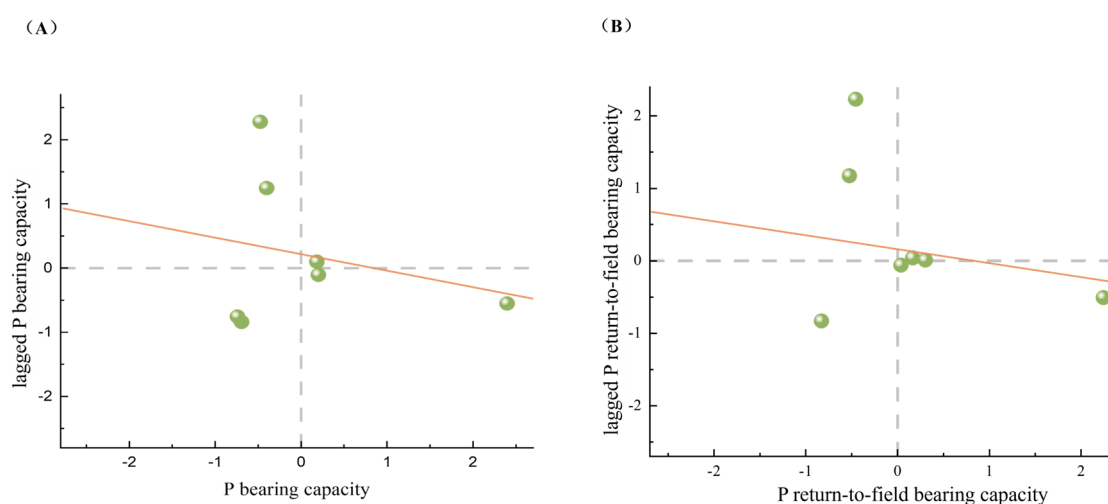


Figure 4. Moran scatterplots for the P bearing capacity (A) and the P return-to-field bearing capacity (B) across eight county-level units in Liaocheng City. The green dots in the picture represent the administrative divisions of Liaocheng City.

4. Conclusions

Using the NUFER mass-balance model, this study quantified N and P flows and assessed the temporal and spatial patterns of bearing capacity in the food system of Shandong Province from 1994 to 2018 and across the

county-level units of Liaocheng in 2019. In this study, N/P bearing capacity was defined as the ratio of potentially recyclable organic nutrients to the N or P contained in primary crop products, reflecting the capacity of internal organic nutrient resources to meet crop nutrient demand. The results showed that N/P bearing capacity in Shandong generally declined during the study period, indicating a weakening match between organic nutrient supply and crop nutrient removal. These temporal patterns occurred alongside changes in crop production, livestock and poultry production, synthetic fertilizer use, urbanization, and socioeconomic conditions. Synthetic N and P fertilizers remained important external nutrient inputs in areas where the modeled organic nutrient supply was lower than crop-product nutrient demand; however, actual fertilizer requirements cannot be determined from these regional ratios alone. Among organic nutrient flows, livestock and poultry manure were the largest potentially recyclable N and P source, followed by crop straw, whereas human excreta made a comparatively small contribution. Scenario analysis confirmed that enhanced recycling of livestock and poultry manure substantially reduced the theoretical demand for synthetic fertilizers, especially P fertilizer, while additional recovery of human excreta produced only minor changes. The one-at-a-time sensitivity analysis showed that the N-related bearing capacity was mainly responsive to atmospheric N deposition and crop-product N content, whereas the P-related bearing capacity was mainly responsive to crop-product P content, livestock P excretion, and the manure return-to-field ratio. At the county scale, clear differences were observed among the Liaocheng administrative units. The N bearing capacity in Dongchangfu District, Linqing City, and Guan County and the P bearing capacity in Dongchangfu District, Shen County, Linqing City, and Guan County were below 1. Yanggu County had the highest P bearing capacity, reaching 3.16, which corresponded to its relatively large livestock and poultry populations and associated manure P generation. Global Moran's I tests did not indicate significant overall spatial autocorrelation among the eight county-level units, whereas local Moran's I identified several county-specific spatial associations.

Overall, improving manure collection, treatment, and return-to-field efficiency is essential for strengthening organic nutrient recycling, reducing dependence on inorganic fertilizers, and promoting sustainable crop–livestock integration.

Supplementary Materials

The additional data and information can be downloaded at: <https://media.scilit.com/articles/others/2608041424325573/BR-26050067-SM.pdf>. References [23–25,27–33,56,57] are cited in the supplementary materials.

Author Contributions

T.Z.: conceptualization, methodology, software; Q.X.: data curation, writing—original draft preparation; J.L. and Y.W.: visualization, investigation; S.M. and M.A.A.: supervision; S.F.A.-E.: software, validation; Z.L. and M.Z.: writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Not applicable.

Data Availability Statement

Statistical data used in this study can be found in the relevant publicly available statistical yearbooks and official statistical sources cited in the manuscript. Data obtained from previously published studies can be found in the corresponding publications cited in the manuscript. Survey data provided by the Shandong Provincial Animal Husbandry Station are available from the authors upon reasonable request, subject to the data-use conditions of the data provider.

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used ChatGPT for language polishing. After using ChatGPT, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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