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RESEARCH ARTICLE

Toward to agricultural green development by multi-objective zoning and nitrogen nutrient management: a case study in the Baiyangdian Basin, China

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KEYWORDS

Agricultural green development, Baiyangdian Basin, environmental emission threshold, partition management

HIGHLIGHTS

- Development of a novel multi-indicator partition optimization method of nitrogen nutrient management.
- Calculation of multi-indicator environmental thresholds for ammonia volatilization, nitrogen surplus and soil carrying capacity in various regions within the basin.
- Recommendation of various regional spatial optimization methods to enhance nutrient management in crop–livestock systems.

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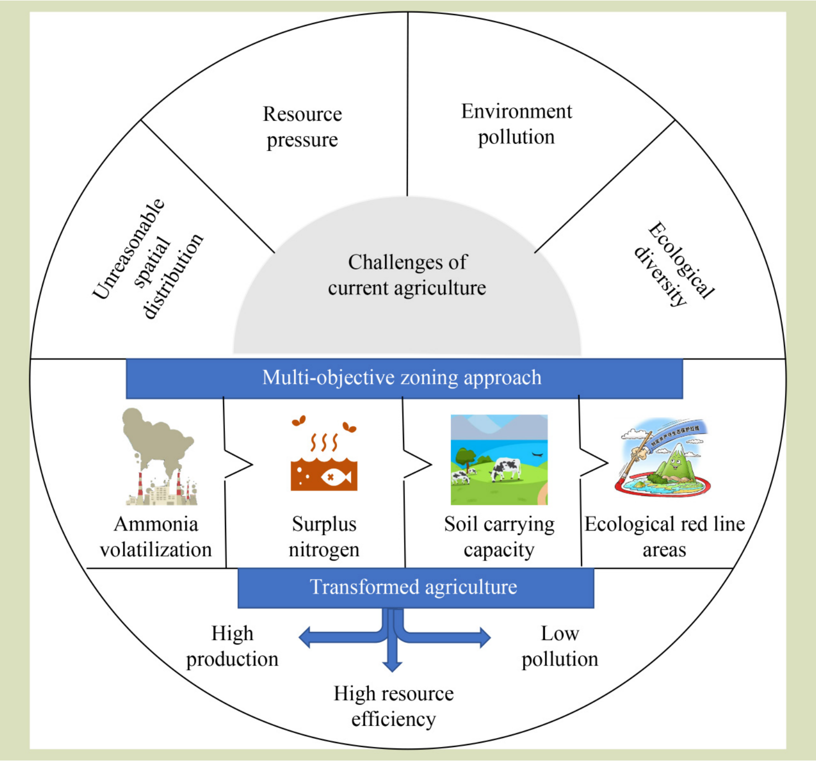
GRAPHICAL ABSTRACT



ABSTRACT

Although China has achieved great advancements toward national food security, the country is still confronted with a range of challenges, including natural resource stress, imbalanced diets and environmental pollution. Optimized management of crop–livestock systems is the key measure to realize agricultural green transformation. However, optimized management of crop–livestock systems that use multi-objective zoning is lacking. This study employed a multi-objective zoning management approach to comprehensively analyze four indicators: ammonia volatilization, nitrogen surplus, soil carrying capacity and ecological red line area. With its significant ecological integrity and a strong emphasis on sustainability, the Baiyangdian Basin serves as a unique and suitable test case for conducting analyses on multi-objective nutrient optimization management, with the aim to facilitate the agricultural green transformation. This study finds that less than 8% of the area in the Baiyangdian Basin meet the acceptable environmental indicator standard, whereas around 50% of the area that had both nitrogen surplus and ammonia volatilization exceeded the threshold. Implementation of unified management, that is, the same management technique across the study areas, could result in an increase of areas meeting environmental indicator thresholds to 21.1%. This project developed a novel multi-indicator partition optimization method, in which distinct measures are tailored for different areas to satisfy multiple environmental indicators. Implementation of this method, could potentially bring more than 50% area below the threshold, and areas with ammonia emissions and nitrogen surplus could be reduced to 15.8%. The multi-indicators partition optimization method represents a more advanced and efficiency-oriented management approach when compared to unified management. This approach could be regarded as the best available option to help China achieve agricultural transformation to improve efficient production and reduce environmental pollution. It is recommended that current policies aimed at nutrient management toward sustainable agricultural development should shift toward the application of multi-indicators partition optimization.

1 Introduction

Food security is no longer the only objective of nutrient management in the current food system. Achieving a sustainable global food system requires a holistic approach to the management of nutrients throughout the food system. Since 2015, the Chinese government has taken the green development of agriculture as the focus of agricultural work and the future development direction[1]. The nutrient management optimization program also addresses the multi-objective challenges within the food system, incorporating the concept of agricultural green development (AGD)[2]. AGD aims to optimize the entire food supply and consumption chain, ensuring the provision of sufficient quantities of nutritious food to all consumers, while concurrently safeguarding the natural environment and the livelihoods of farmers[3]. In the pursuit of AGD, the quality of both human living environment (habitation) and the natural environment (habitation surroundings, including water, air and soil) become highly important[4]. Excessive nitrogen input into agriculture systems has caused environmental problems such as atmospheric pollution, loss of biodiversity and degradation of water[5,6]. Meanwhile, the development of intensive animal farming has further caused the separation between crop and livestock sectors, leading to additional hotspot areas prone to pollutant discharge[7]. In Europe, designated vulnerable areas of nitrate have been established based on the Nitrate Act and Water Act, which can mitigate the risks of nitrate pollution by using precise zoning management for nitrogen[8,9]. The US Environmental Protection Agency (EPA) has enacted the Water Purification Act and the Safe Drinking Water Act, which set nitrate content thresholds for drinking water and surface water. By integrating watershed models, the EPA assesses the carrying capacity of agriculture and animal husbandry activities in a given area to explore optimal nutrient management measures at both regional and farm levels, with the aim of preventing and controlling environmental pollution within watersheds[8].

In addition to the aquatic environment, agriculture and livestock activities also have an impact on the atmospheric environment. In an effort to mitigate atmospheric pollution for safeguarding human health, the EU has set emission limits for air pollutants[9]. These limits guide member countries in optimizing their agricultural and livestock management measures to control air pollutants from these sources. There is a significant concern as ammonia from agriculture contributes to 80% of the total emissions, which can influence the levels of $PM_{2.5}$ in the atmosphere. To address the pollution issues arising from high ammonia emissions from agriculture, the Dutch Supreme Court has imposed a nationwide prohibition on livestock and poultry production. However, implementation of emission reduction measures that solely focus on a single indicator has led to production shutdowns, biodiversity losses, and even caused civil disturbances such as farmer protests and traffic jams[10]. The concept of AGD was developed to achieve a more sustainable agricultural framework[3]. At present, there have been relevant reports on the thinking and planning of AGD[11,12]. Recent studies have focused on the definition of its parameters and understanding its theory of framework and major components[4,11]. These studies can be used in the development and planning of AGD[13]. However, in an effort to ensure food security, all aspects of environmental protection should be considered in order to achieve AGD. Therefore, it is necessary to start from the comprehensive multi-indicators to optimize nutrient management and accelerate the transformative journey in agriculture.

Developing an ecological and environmental multi-indicator system to manage nutrients is one of the important components of achieving a green ecological environment. While some studies are still in the early stages of development exploring ideas and frameworks for sustainable agricultural development[11,12,14], many studies focus on nutrient management in crop–livestock systems in watersheds. The majority of these studies are unable to simultaneously balance environmental protection and efficient nutrient utilization. For example, recent recommendations for crop types, livestock density classification, and other management methods were typically based on addressing specific issues such as nitrate pollution or water quality[15–17]. However, when nutrient management aims to simultaneously protect soil, water and the atmosphere, conflicts may arise. These conflicts often result from the complicated interplay between measures targeting air or water loss and the necessary adjustments required in different spatial areas. Some researchers, such as Jin et al.[18,19], have made progress by dividing vulnerable nitrate areas in China on a national scale and planning regional spatial nutrient management strategies to improve nutrient use efficiency while reducing losses. However, the delineation of spatial regions within a basin that can satisfy multiple environmental indicator constraints concurrently remains unclear. Therefore, there is an urgent need to establish a comprehensive methodology for delineating environmental regions that consider multiple objectives and constraints. This approach will enable highly effective and targeted agricultural green management at the basin scale.

The Baiyangdian Basin is an important part of the integrated and coordinated development of the Beijing-Tianjin-Hebei urban agglomeration. It serves as a crucial ecological water resource, having a vital role in supporting the livelihood and economic growth of the residents around the Xiongan New Area. Due to the implementation of a series of environmental protection policies in Baiyangdian, there have been substantial changes in the production of the crop–livestock systems within the basin. Current research on the Baiyangdian Basin mostly focuses on various aspects, such as assessing water quality[20], evaluating the water environment[21], and studying ecological services and functional zoning. Furthermore, a limited number of studies have also highlighted the issue of nutrient emissions from crop–livestock systems in this region[22]. These studies have explored the impact of agricultural nutrient losses on water quality[23] and the spatial distribution of unused nitrogen[24]. There is a lack of research on managing nutrients in crop–livestock systems under the constraints of multi-environmental indicators. Therefore, under the background of relatively strict environmental requirements in Baiyangdian, it has become imperative to develop nutrient optimization management methods that meet multiple environmental index thresholds to facilitate the harmonious coexistence of urbanization green agriculture and livestock production.

By using the NUFER (nutrient flows in food chains, environment and resources use) model, we have explored the nitrogen correlated environmental indicators and their associated thresholds. The study aimed to (1) select key environmental indicators and construct a multi-objective zoning and nitrogen nutrient optimization management model; (2) quantify the thresholds for these environmental indicators and determine the current levels of environmental emissions in the Baiyangdian Basin; and (3) analyze different scenarios and their potential for reducing environmental impacts, thus realizing AGD.

2 Materials and methods

2.1 The study area

The Baiyangdian Basin encompasses portions of Hebei, Beijing and parts of Shanxi. Its topography is intricate, characterized by three major landforms that run from west to east: mountains, plains and depressions. It is located in the warm temperate continental monsoon climate zone, with four distinct seasons. The annual mean temperature ranges from 9.3 to 12.2 °C, and the average yearly precipitation is about 550 mm. There are numerous river networks in the area, comprising eight subbasins, including the Baigouyin River Basin with seasonal water flow, the Fu and Xiaoyi Rivers Basin with year-round water supply[23]. The study area is geographically divided into two main regions: a mountainous area consisting of 17 counties in the north-west part of the basin and a plain comprising 21 counties in the south-east part of the basin.

2.2 Transition of agricultural green development and multi-indicators optimization

China has made great progress in achieving grain self-sufficiency and enhancing food security[25]. However, Chinese agriculture still needs to overcome multiple challenges, such as environmental pollution, resource constraints and many Chinese people still consume an unbalanced diet. To address these current challenges within agriculture systems, it is necessary to adopt a system-based approach that considers many aspects of agriculture. This study aimed to explore the multiple objective zoning and nitrogen management approach to achieve the transformation of agriculture (Fig. 1).

2.2.1 Indicator selection

To optimize the efficiency of crop–livestock systems, consideration should be given to a range of environmental indicators that directly impact human health, the production of high-quality goods, and environmental characteristics. We identified four specific indicators, namely ammonia volatilization, surplus nitrogen, soil carrying capacity and ecological red line areas, which are pivotal for optimizing the crop–livestock systems. Specifically, the ammonia indicator focuses on the release of ammonia into the atmosphere, a significant factor in air quality and ecological balance. Surplus nitrogen refers to the excess nitrogen in agricultural systems beyond what is actually needed by crops. It constitutes a factor influencing water environment and air quality. Soil carrying capacity refers to the ability of the local land to support the quantity of livestock without causing ecological issues, which is a critical factor in the distribution of livestock. The ecological red line areas refer to designated regions where strict environmental protection measures and land-use controls are enforced to safeguard critical ecosystems, conserve biodiversity and protect natural resources.

2.2.2 Determining the threshold of environmental indicators

The importance of each indicator should be evaluated in the context of local conditions and specific circumstances. Different regions have diverse environmental, social, human and economic factors that influence the significance of these indicators. In this study, we used the NUFER model to quantify

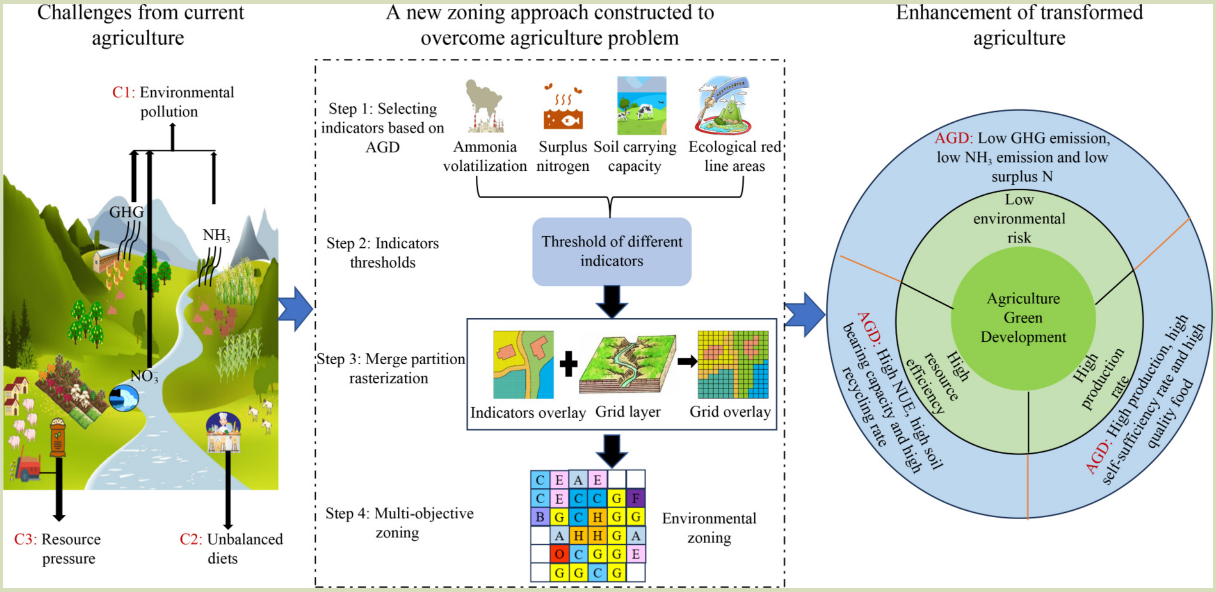


Fig. 1 Conceptual framework of transformed agriculture.

NH_3 fluxes in the Baiyangdian Basin. The NUFER model, developed based on a mass balance methodology, enables the analysis of N fluxes in various sectors, including crop production, animal production, food processing, and food consumption, at different spatial scales, such as national, provincial, agroecological zones and county levels. The detailed calculation methods of the NUFER model can be found in Ma et al.[26]. In this study, our focus is on crop–livestock systems, which encompass the emission of NH_3 from the manure management chain and cropland. This is because NH_3 is an important precursor for forming $PM_{2.5}$ and excessive levels of $PM_{2.5}$ can have adverse effects on human health[27,28]. Therefore, management of ammonia emissions could mitigate the human health risks associated with $PM_{2.5}$ pollution. A correlation between ammonia emission and $PM_{2.5}$ was established through the utilization of geographically weighted regression analysis. The correlation allowed us to classify the Baiyangdian Basin into two distinct regions: NH_3 emission sensitive and non-sensitive regions. Based on population density, the NH_3 emission sensitive regions were further classified into three categories, each with its own calculated threshold for ammonia volatilization. The threshold value was determined through the application of a functional relationship between the Sustainable Development Goals index score and ammonia volatilization data[29]. Nationally uniform ammonia emission thresholds of 31 $kg \cdot ha^{-1}$ were applied to the non-relevant regions (Table 1). The distribution of ammonia volatilization threshold was derived by overlaying the population density distribution with a raster map of cultivated land.

Nitrogen surplus in cropping systems is defined as the difference between the N input and the harvested N output, which is a useful indicator for improving crop N management and controlling N pollution in watersheds. The nitrogen surplus was calculated based on the nitrogen balance calculation provided by the NUFER model. Different regions have various factors such as river proximity, slope, and cultivated land that influence the threshold of nitrogen surplus. The grid maps illustrating nitrogen surplus at various levels were generated by overlaying grid maps of river proximity, slope and cultivated land grid maps. The threshold value of nitrogen surplus is determined by the value of nitrogen in the watershed and the critical value of runoff or leaching in the nitrate vulnerable zone within the county. Nitrogen surplus in the watershed was first determined by overlaying the grid maps representing slope and river distance in the Baiyangdian Basin. The threshold values for different sub-watersheds are derived from the study of Yang et al.[30] (Table 2).

$$\text{Surplus } N_{water} = N_{water} \times (1 - R_{loss}) / R_{runoff} \times R_{class} \tag{1}$$

where, Surplus N_{water} is the surplus nitrogen thresholds in different subbasins within various regions at a specific time (t),

Table 1 Threshold of ammonia volatilization in different grade regions

Region		Population density ($person \cdot km^{-2}$)	Ammonia emission threshold ($kg \cdot ha^{-1}$)
NH_3 emission sensitive regions	High density	> 1000	24
	Medium density	500–1000	27.5
	Low density	1–500	31
Non-sensitive regions		–	31

Note: “–” indicates no data.

Table 2 Threshold of surplus nitrogen in different grade regions

Region	Slope (°)	Distance (m)	Surplus N threshold (t)		
			Subbasin 1 (Baigouyin River)	Subbasin 5 (Fu River)	Subbasin 7 (Xiaoyi River)
Steep, close	> 3	⩽ 2000	1.49×10^5	–	–
Slow, close	⩽ 3	⩽ 2000	2.47×10^4	2.12×10^3	2.74×10^2
Steep, far	> 3	> 2000	1.50×10^5	5.1×10^1	–
Slow, far	⩽ 3	> 2000	3.38×10^5	1.77×10^3	4.47×10^2
Total basin	–	–	6.61×10^5	3.94×10^3	7.21×10^2

Note: “–” indicates no data.

N_{water} is the nitrogen thresholds in water of different subbasins at the same time (t), R_{loss} is the loss ratio of runoff into subbasin water (%), R_{runoff} is the proportion of runoff to nitrogen surplus in different subbasins (%), and R_{class} is the proportion of different subbasins in different regions (%).

Then the watershed without water is determined by the critical value of the national nitrate vulnerable zone. In the overlapped area of the watershed and county, the lowest nitrogen surplus value was selected as the final nitrogen surplus threshold as:

$$\text{Surplus } N_{waterless} = N_{leaching}(N_{runoff})/R \times \text{Area} \times 1000 - \text{Surplus } N_{water} \quad (2)$$

where, Surplus $N_{waterless}$ is the surplus nitrogen threshold specific to waterless watershed (t), $N_{leaching}$ (N_{runoff}) is the critical value of nitrogen leaching or runoff in a nitrate fragile zone ($kg \cdot ha^{-1}$), R is the nitrogen leaching or runoff as a proportion of nitrogen surplus (%), and Area is the area of cultivated land in the county (ha).

Soil carrying capacity is an environmental risk index for livestock. The level of soil carrying capacity indicates whether the local land can support the quantity of livestock without causing ecological issues. Soil carrying capacity refers to the ratio of nitrogen excreted by livestock to the nitrogen harvested by crops in the area as:

$$N_{soil} = N_{manure}/N_{plant} \quad (3)$$

where, N_{soil} is soil carrying capacity, N_{manure} is the N content from livestock manure (t), and N_{plant} is N absorbed by plants (t). The threshold value of soil carrying capacity was 1[23]. If N_{soil} is less than 1, there is a high soil carrying capacity. This means these areas can absorb the excrement of livestock without negative consequences. If N_{soil} exceeds 1, there is a lower soil carrying capacity and these areas are overloaded. If N_{soil} is greater than 2, there is a severe overload of the carrying capacity of the land.

2.2.3 Zoning of Baiyangdian Basin

According to the comparison between the current situation and the threshold value, areas that exceeded the threshold are classified as high, while areas that were below the threshold value are classified as low. We applied this methodology to three indicators: ammonia emission, surplus N and soil carrying capacity, resulting in eight categories. In addition, precise ecological redline areas have been delineated to protect their natural habits. Therefore, the Baiyangdian area is divided into eight overlay areas, each representing a unique combination of the three indicators, along with one ecological red line area (Fig. 2). Then we adopt corresponding optimization models specifically for regional characteristics.

The nine regions are categorized as: A, safe zone, where the levels of ammonia volatilization, surplus nitrogen, and soil carrying capacity do not exceed the threshold values; B, overloaded zone, where soil carrying capacity exceeds the standards while other indexes remain within limits; C, high ammonia zone, where the index for ammonia volatilization exceeds standard levels, but all other indexes fall within

	Ammonia emission		Surplus N		Soil carrying capacity		Ecological red line area
Zone	Low	High	Low	High	Low	High	
A	●		●		●		
B	●		●			●	
C		●	●		●		
D		●	●			●	
E	●			●	●		
F	●			●		●	
G		●		●	●		
H		●		●		●	
O							●

Fig. 2 Level of indicators in different zones (low, below the threshold; high, exceeding the threshold; A, safe zone; B, overloaded zone; C, high ammonia zone; D, high ammonia overload zone; E, high surplus zone; F, high surplus overload zone; G, high ammonia and surplus nitrogen zone; H, high-risk zone, and O, ecological red line area).

acceptable ranges; D, high ammonia overload zone, where both ammonia volatilization and soil carrying capacity exceed the standards; E, high surplus zone, where surplus nitrogen index exceeds the standard, other indexes are within the standard ranges; F, high surplus overload zone, surplus nitrogen and soil carrying capacity exceed the standards; G, high ammonia and surplus nitrogen zone, where both ammonia volatilization and surplus nitrogen exceed the standards; H, high-risk zone, where ammonia volatilization, surplus nitrogen and soil carrying capacity all exceed the standards; and O, ecological red line zone, where cropping and livestock production are prohibited to safeguard biodiversity. The ecological red line area has been delimited by the state, with farming activities such as cropping and livestock production are prohibited, and this area should be avoided when considering the adjustment to agricultural practice and location.

2.2.4 Scenario optimization

Based on the current emission status of environmental indicators in crop–livestock systems, three scenarios were developed to evaluate potential emission reductions: (1) CS, the current situation scenario in which a comprehensive assessment of environmental indicators in the Baiyangdian Basin was made based on statistical data; (2) UT, the government's highly-recommended unified management technology in which the whole region adopts the model of integrating agriculture and livestock, mainly promoted by the state, to facilitate the recycling of nutrients in crop–livestock systems, aiming to reduce nutrient input requirements and promote efficient nutrient recycling; and (3) ZM, a management technology applications based on zoning partition management which is based on the unified policy, targeted emission reduction technologies are employed for zone-specific optimal management based on the distinctive characteristics of each zone (Table 3).

3 Results

3.1 Classification standard and status of environmental indicators across different areas within the Baiyangdian Basin

There are four environmental indicators that are utilized for partitioning. Due to the distinct characteristics of the counties, the classification threshold of each environmental indicator is unique. Ammonia emission indicators are highly inversely correlated with population density. Therefore, high population density areas (southern plains) have a low ammonia emission threshold and low population density areas (mountainous area and eastern plains) have a higher threshold. Given that the nitrogen surplus threshold used for the partitioning process is determined by slope and river distance, counties located in eastern areas have a high nitrogen surplus indicator threshold and counties located in western areas have a low threshold. The ecological red line area and soil carrying capacity are regulated by the government, meaning that the red line area and soil carrying capacity threshold remain consistent across all counties in the Baiyangdian Basin.

The spatial distribution of NH_3 emissions at a county scale in the Baiyangdian Basin is shown in Fig. 3. Only four counties located in the eastern basin did not exceed the established threshold in the plain area. Also, there is a substantial accumulation of nitrogen in this region; specifically, 40% of counties had excess nitrogen levels surpassing 200 $kg \cdot ha^{-1}$. The primary reason for this nitrogen accumulation in the plain areas is the high concentration of crop and livestock production in these regions, leading to substantial nutrient emissions and low nitrogen use efficiency. For soil carrying capacity, five counties located in the mountainous area have a soil carrying capacity that is slightly above the threshold. Tang County located in the central basin, a major producer of

Table 3 Emission reduction technologies in different zones

Scenario	Zone	Emission reduction technology
UT	B–H	Balanced nutrient supply and demand
ZM	B	Remove part of the livestock population
	C	Frequent manure removal technique, covered storage, and reactor composting
	E	Improvement of fertilization methods, application of new-type fertilizers, and integration of water and fertilizer
	F	Remove part of the livestock population
	G	The whole chain emission reduction technology of crop–livestock systems
	H	Remove part of the livestock population

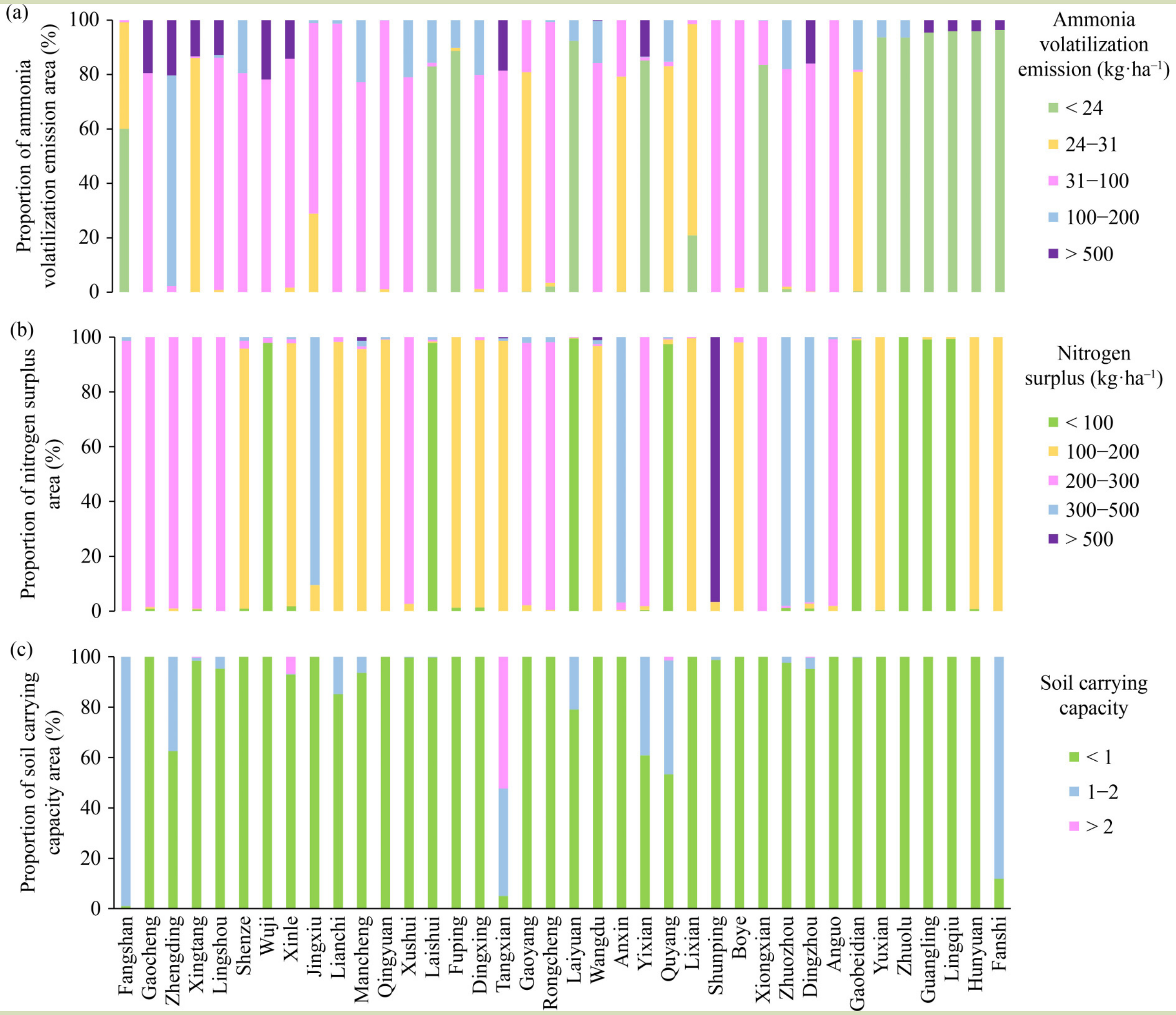


Fig. 3 Proportion distribution of environmental indicators in the Baiyangdian Basin (%): (a) ammonia emission, (b) surplus N, and (c) soil carrying capacity.

livestock products, significantly surpassed this threshold. Taking into account multiple indicators, appropriate measures should be implemented in areas that exceed the threshold in order to reduce nutrient losses and emissions.

3.2 Environmental zoning for crop–livestock systems

Environmental zoning for crop–livestock systems is a valuable tool that provides clear criteria, principles and procedures. It can support differentiated regional management according to different environmental emission from of crops and livestock, and the environmental thresholds of different regions. The rationality of environmental zoning, based on environmental indicators, lies in its ability to effectively capture and reflect the spatial distribution of key environmental parameters. By comparing these indicators, the zoning process can delineate distinct regions with varying degrees of environmental parameters, enabling targeted management and interventions. This approach enhances the allocation of resources, optimizes pollution control strategies and facilitates sustainable development by addressing the specific environmental challenges in each zone. In addition, it promotes precision and efficiency in decision-making, aligning regulatory measures and conservation efforts with the unique characteristics of each zone.

Based on multi-objective environmental thresholds, different environmental regions were identified for crop–livestock systems in the Baiyangdian Basin. For the convenience of administrative management, counties were grouped into eight distinct zones (Fig. 4). Specially, the high ammonia and surplus nitrogen zone (G) are mainly concentrated in the southern plains region of the basin, covering about 66% of the total plain area (Table 4). The mountainous areas had a relatively complexity, with a slightly higher proportion of the high ammonia zone (C). This is mainly due to the presence of less arable land and a higher concentration of livestock farming, resulting in increased ammonia emissions from livestock. From the perspective of various subbasins, the environmental emissions analysis reveals that the double-high zone, high ammonia and high nitrogen surplus (G), have the largest proportion across all eight zones.

3.3 Optimizing nutrient management and recommendations

The optimization results indicate that the UT scenario, which integrates the crop–livestock systems to reduce nutrient input, has led to a significant reduction in ammonia volatilization and surplus nitrogen emissions in all counties in the Baiyangdian Basin. Specifically, ammonia emissions have decreased by a third and nitrogen surplus has fallen by almost a half (Fig. 5). However, despite these notable improvements, the levels still exceeded safety limits. After the implementation of unified technology management, only eight counties in the Baiyangdian Basin have made adjustments. Although a unified technology management approach is highly recommended by the government, it cannot meet the emission reduction requirements for all regions due to variations in ecological conditions. To further achieve emission reduction goals, it is necessary to apply zonal emission reduction technology.

To identify feasible and highly effective mitigation measures for each part of the Baiyangdian Basin, all available mitigation options were considered. The optimal measures for specific

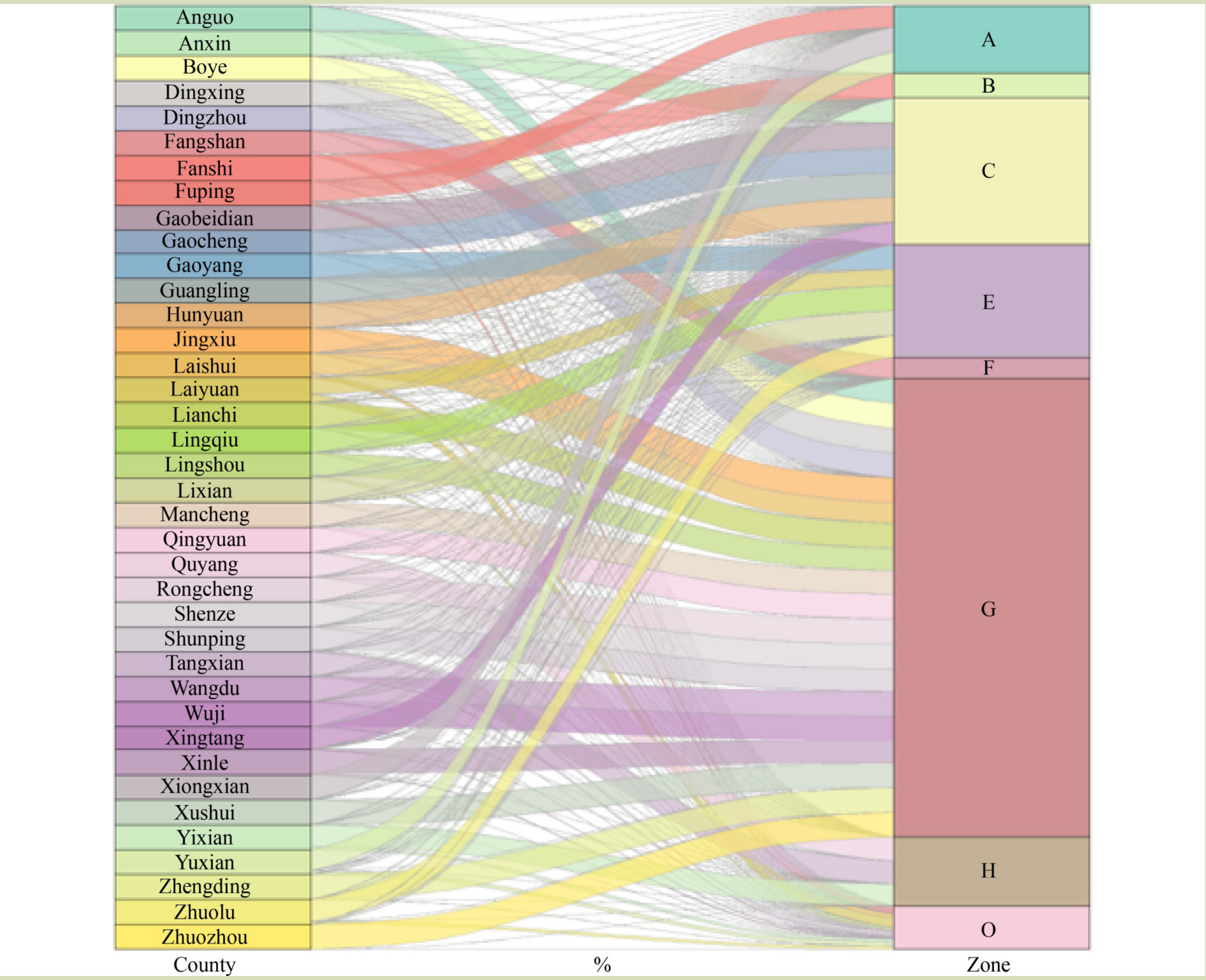


Fig. 4 Environmental zoning for the crop–livestock systems in the Baiyangdian Basin (A–O represents the meaning as shown in Fig. 2).

Table 4 Area proportion of different environmental zones in the crop–livestock systems of Baiyangdian Basin (%)

Zone and index characteristics		A (Surplus N low; ammonia emission low; non-overload)	B (Surplus N low; ammonia emission low; overload)	C (Surplus N low; ammonia emission high; non-overload)	E (Surplus N high; ammonia emission low; non-overload)	F (Surplus N high; ammonia emission low; overload)	G (Surplus N high; ammonia emission high; non-overload)	H (Surplus N high; ammonia emission high; overload)	O (Prohibited cultivation)
Topography	Mountain	15	7	18	16	3	14	16	11
	Plain	5	–	18	10	–	66	–	1
Basin	Baigouyin River	–	–	13	6	10	44	14	13
	Ping River	–	–	7	–	–	84	9	–
	Bao River	–	–	5	–	–	60	33	2
	Cao River	–	–	1	–	–	75	14	10
	Fu River	–	–	6	–	–	93	–	1
	Tang River	–	–	11	22	–	45	17	5
	Xiaoyi River	–	–	2	38	–	60	–	–
	Zhulong River	5	–	17	9	–	52	13	4

Note: "–" indicates no data. A, safe zone; B, overloaded zone; C, high ammonia zone; D, high ammonia overload zone; E, high surplus zone; F, high surplus overload zone; G, high ammonia and surplus nitrogen zone; H, high-risk zone

areas were selected based on their mitigation efficiency, practical applicability and implementation cost. After implementing zoning management, the overload zones (B) can achieve compliance with the environmental threshold by reducing of livestock (including poultry) production by 5%. By utilizing rapid cleaning and drying technology in enclosures, covering storage and reactor composting the high ammonia zone (C), Anxin, Gaobeidian and Guangling Counties, distributed around the basin, all remain within safe environmental thresholds. In the high surplus zone (E), the implementation of full chain emission reduction technology for farmland will bring environmental emissions below the threshold values in 80% of counties. A reduction of 25% in livestock numbers within the high surplus overload zone (F) will effectively bring all counties within this area below safety thresholds. The high ammonia and surplus nitrogen zone (G) requires the adoption of a comprehensive emission reduction technology for crop–livestock systems. This implementation would lead to 32% of the area becoming safe zones, 36% of the areas becoming single-factor exceedance areas, with the remaining 32% remaining unchanged. In high-risk areas (H), specific reductions in livestock production are necessary to mitigate the environmental risk. Quyang and Yixian Counties, located in the middle of the basin, need to reduce livestock production by 5%, while Tang County should undertake a significant reduction of 70%. These targeted reductions will contribute to achieving a more sustainable agricultural systems in these areas. Additionally, the entire livestock and poultry supply chain should implement emission reduction technologies to meet environmental safety standards.

Based on the above results, it can be seen that after implementing UT the proportion of counties within safe districts increased from 8% to 21%, while the high-risk zone (double-high zone) only decreased by less than 6% (Fig. 6). Continuing with further application of ZM, over 55% of the counties in the Baiyangdian Basin have achieved more environmentally-friendly emissions, with all three indicators falling within the threshold values. However, there are still some areas that exceed the safety threshold. Specifically, 10.5% of counties continued to have high ammonia emissions, 18.4% have high nitrogen surplus and 15.8% have both.

4 Discussion

4.1 The development and use of environmental thresholds

In 2009, Steffen et al.[31] provided the concept of planetary boundary, which defines a safe operating space for humanity. In that study, nine planetary boundaries were identified that humans should not exceed to avoid potential risks[31]. The latest research shows that six indicators have crossed the planetary boundary[32]. After the planetary boundaries have been established, some studies have updated and extended this

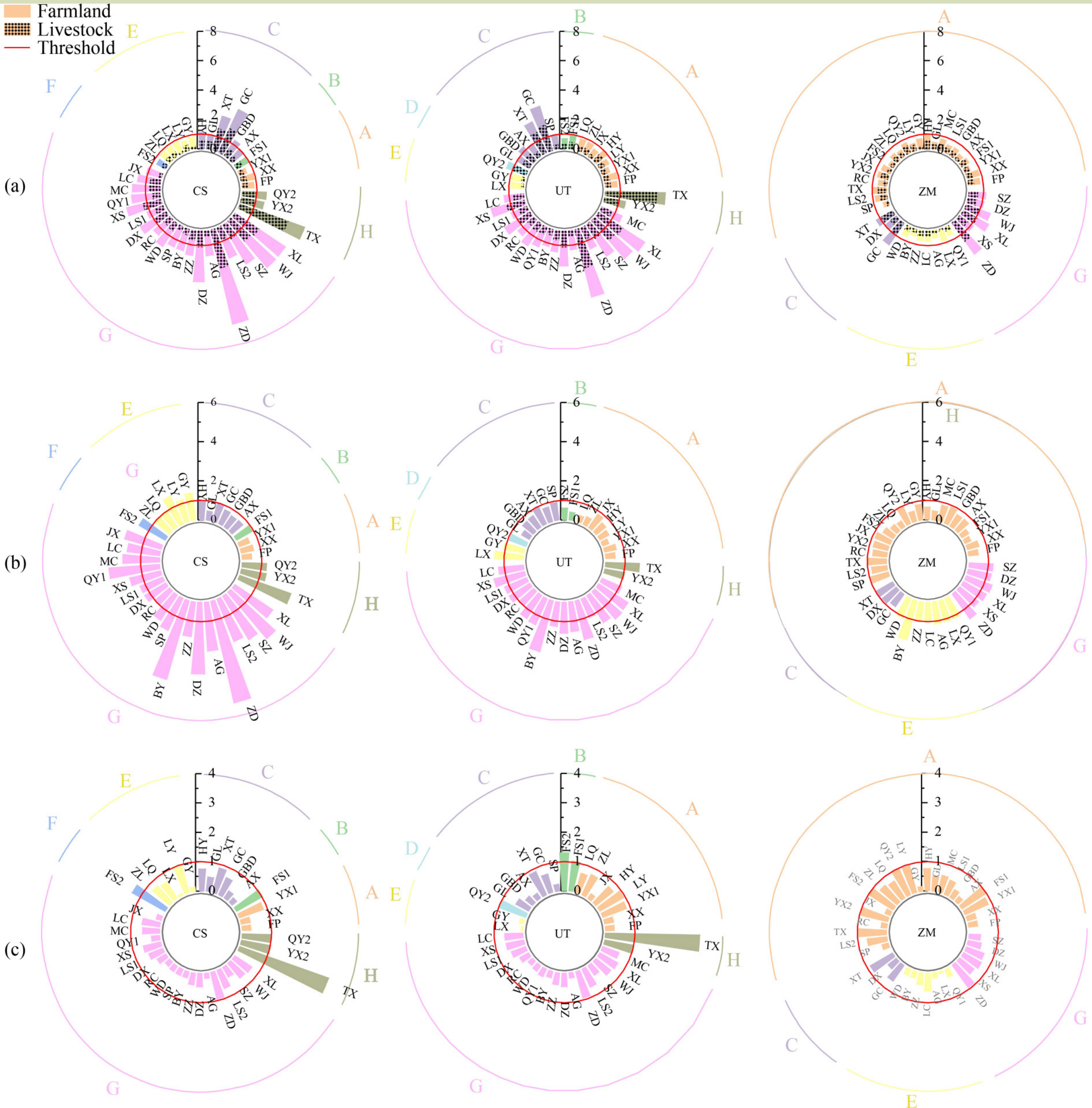


Fig. 5 Changes of environmental indicators under different scenarios: (a) ammonia emission, (b) surplus N, (c) soil carrying capacity.

planetary boundary framework. Schulte-Uebbing et al.[33] employed a spatial model to establish regional boundaries for agricultural nitrogen surplus by incorporating eutrophication thresholds in terrestrial and aquatic ecosystems and nitrate levels in groundwater. The results indicate that the current nitrogen surplus has already exceeded these thresholds in eastern China[33]. Although significant progress has been made in quantifying environmental thresholds at both global and national scales, the watershed, regarded as the most suitable management unit, presents considerable challenges in determining these environmental thresholds. Currently, the determination of environmental indicators in watersheds is largely based on single perspectives, such as irrigation, farmland input or water pollution caused by different crop–livestock systems[30,34,35]. Achieving accurate environmental management of watersheds requires an integrated approach that is consistent with various environmental objectives. The EU has adopted such a comprehensive strategy that takes into account agricultural inputs and losses in connection with factors like biodiversity, algal bloom, and drinking water quality, as emphasized by Vries et al.[36]. However, in Europe, there is still a lack of

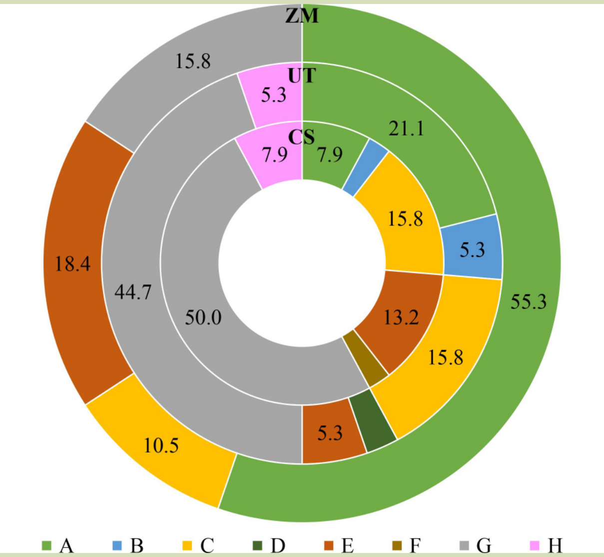


Fig. 6 Proportion of different regions in different scenarios (%) (A–H represents the meaning as shown in Fig. 2).

localized environmental indicators, resulting in continued reliance on globally or nationally uniform thresholds for managing the environment. Therefore, localized environmental indicators based on multi-objective criteria as developed in this study can contribute to effective environmental management. A comprehensive localized environmental threshold can accelerate progress for achieving agriculture green transformation and optimized management practices.

4.2 Environmental zoning of nutrient management in basin agriculture

Sustainable development in crop–livestock systems is partly influenced by the optimal management of nutrients. Several studies have proposed that there is a need to enhance scientific management of agriculture in areas with intensive human activities within a watershed[37]. Current research mostly focuses on emission reduction technologies related to fertilizer management and the application of organic fertilizer[38–40]. These emission reduction technologies could contribute to restructure the relationship with crop–livestock systems, offering an optimal way to improve the management of nutrients[41–43]. Although there is a growing availability of technologies aimed at reducing emissions from crop–livestock systems, the diversity in planting practices, breed structures, management methods, environmental conditions and nutrient management in crop–livestock systems highlights the need for adapting to local contexts and employing suitable technologies. Therefore, environmental zoning methodologies will be a vital prerequisite for the efficient implementation of emission reduction techniques. Currently, zoning methodologies often rely on land-use types or ecologically sensitive areas, but they lack a multi-objective based partitioning approach[44,45]. Our proposed multi-indicator, environmental zoning method for crop–livestock systems can be optimized by utilizing emission reduction technologies that are targeted based on the emission characteristics of the various indicators of each region. This approach avoids the need for strict unified management technology to achieve the threshold of all indicators across the entire region, resulting in cost savings. Simultaneously, while ensuring negative impacts on other zones, the nutrient management mode of each small zone can only be altered to achieve a balance between crop and livestock production development and environmental sustainability. Although some studies have also tried to implement strategies to reduce environmental pollution based on AGD, they have always focused on a national scale[46,47]. The national studies could offer initial insights into AGD and develop feasible policies for achieving multiple national development goals. Although the national policies and strategies can establish pathways for achieving AGD, the implementation of these strategies is often challenging. Given that watersheds serve as optimal management units for coordinating food production and environment preservation, the implementation of a system approach through the watershed can be extended nationwide. It can provide a methodology to assist other watersheds to achieve transforming agriculture.

4.3 Green transformation of agriculture and strategies recommendations for watershed

The watershed zoning management approach that we have developed considers various aspects of environmental sustainability within the context of agricultural green transformation. We have devised a zonal method based on multiple environmental indicators and proposed optimization measures for effective zonal management. Corresponding emission reduction technologies are applied in environmentally sensitive areas of the watershed. Achieving a green transformation in watershed crop–livestock systems requires not only environmental considerations but also the balance of productivity and economic benefits. Therefore, future research on watershed green transformation should explore the synergistic development of crop–livestock systems, considering both productivity and environmental concerns, and possibly incorporating economic factors into the equation.

Additionally, nutrient optimization management should account for the necessity of coordinating regional planning to facilitate the reintegration of crop–livestock systems, mitigate nutrient accumulation in regions with limited land availability, and minimize pollution transfer between areas. This comprehensive approach aims to achieve an all-encompassing green transformation of crop–livestock systems.

In recent years, the Chinese Government has advocated the integration of agriculture and livestock development. Since 2017, relevant policies and measures have been introduced, such as the Implementation Plan for the Construction of Fruit, Vegetable and Tea organic Fertilizer Replacement Demonstration Zone and the Implementation Plan for Pilot Counties of Green Planting and Breeding Circular Agriculture. From the perspective of agriculture–livestock coupling, resource conservation, overall efficiency improvement, and promotion of green development can be achieved through strategies such as reducing fertilizer inputs and enhancing nutrient cycling. Our scenario analysis results indicate that the government’s highly-recommended unified management technology can reduce emissions to some extent, but it cannot ensure the environmental security of whole regions or basins. The optimal nutrient management approach involves the integration of agricultural and animal husbandry development with environmental considerations, aiming to achieve harmony and unity between crop and livestock production practices, and environmental management for a range of ecosystem services. By selecting management methods based on the specific characteristics of different regions and following the principles of employing the most effective and least emission-intensive technologies, it is possible to achieve maximum emission reduction while minimizing the need for large-scale adjustments caused by uniform policies.

In coming stages, it is essential to emphasize the necessity of coordinated regional spatial planning, which will make a pivotal contribution to facilitating the seamless reintegration of crop–livestock systems. This integration aims to alleviate nutrient accumulation in areas where land availability is constrained and mitigate the transfer of pollutants between different areas. Currently, diet structure is also a major factor affecting the green transformation of agriculture, and excessive meat consumption will increase the risk of human disease. Meat production requires large amounts of feed, water and land resources, and the excessive use and waste of these resources will also lead to serious environmental pollution and ecological damage. Additionally, a comprehensive comparative analysis that considers economic, social and environmental aspects is imperative to strike a harmonious equilibrium between ecological and economic progress. This analysis will serve as a crucial framework to guide decision-making and determine the optimal pathways for achieving a comprehensive and all-encompassing green transformation in the agricultural sector.

5 Conclusions

This study proposes a novel approach for eco-environmental regionalization at the basin scale, with a focus on agricultural green transformation. It establishes the thresholds for various indicators, providing precise and optimized solutions for nutrient management in crop–livestock systems, particularly under the stringent environmental control policies in the Baiyangdian Basin, where overall environmental emission limits are set at low levels. The Baiyangdian Basin was partitioned into nine regions using a multi-objective regionalization method, with the highest proportion of ammonia volatilization and surplus nitrogen zone accounting for 50% and a safety zone accounting for less than 8%. The implementation of a unified management approach, integrating crop and livestock production, resulted in an increase in the safety area to 21.1%. However, the effect of a reduction in high ammonia volatilization and surplus nitrogen zones was not significant. To further enhance the management strategy, partition management technology was introduced, resulting in a 50% increase in the safety zone and a reduction in the proportion of double-high (excessive ammonia volatilization and surplus nitrogen) zones of 15.8%. This system approach not only provides an effective way to address the challenges in Baiyangdian Basin but also offers a potential way to meet the current challenges in agricultural systems in China and thereby help the country to transform to a more environmentally-friendly agriculture systems. Agriculture transformed in such a way can protect natural resources, reduce pollution and improve resource use efficiency, while maintaining food security.

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Compliance with ethics guidelines

Xiaomeng Zhang, Xiangwen Fan, Wenqi Ma, Zhaohai Bai, Jiafa Luo, Jing Yang, Ling Liu, Jianjie Zhang, and Lin Ma declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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