

Article

The Lag Effect of National Nitrogen Management on Nitrogen Use Efficiency and Greenhouse Gas Emission

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Abstract

Effective nitrogen (N) management is essential for ensuring food security, promoting agricultural sustainability, and addressing climate change due to the rise in fertilizer use since the 20th century. However, environmental improvements from N management are subject to uncertainties and time lags. In this study, we analyzed data from 113 countries, focusing on N use efficiency and greenhouse gas emissions as key indicators. Our results illuminated a notable lag effect between improvements in these two indicators at the global scale, posing formidable challenges in achieving timely environmental benefits through N management strategies. We categorized countries into four groups based on agricultural sustainability, offering insights into the environmental impacts of various N management practices. Nations prioritize N management differently, reflecting the intricate interplay between socio-economic determinants and environmental considerations. Adopting integrated N management practices, which balance agricultural productivity and environmental conservation, represents an indispensable imperative for the advancement of sustainable agriculture.

Keywords: environmental Kuznets curve; greenhouse gases; nitrogen use efficiency; agronomy management; climate change



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1. Introduction

Since the early 20th century, the invention and application of the Haber–Bosch process, which converts stable nitrogen (N) gas to reactive N, has greatly increased global crop yields and fed a great population [1,2]. The global population is projected to reach 9.7 billion by 2050, meaning that growing demand will greatly challenge food security [3]. Ensuring access to sufficient, safe, and nutritious food is essential. Today's food systems face numerous challenges, including climate change, natural resource depletion, and inefficient production [3,4]. Indeed, global food security and food system sustainability are critical components of the United Nations' Sustainable Development Goals (SDGs), including SDG 1-No Poverty, SDG 2-Zero Hunger, SDG 3-Good Health and Well-being, SDG 13-Climate

Action, and SDG 15-Life on Land. Despite the impressive crop yields achieved through the use of fertilizer inputs, a large amount of reactive N has entered the terrestrial and aquatic ecosystems, bringing a series of unintended environmental impacts [5–7]. Also, the application of synthetic fertilizers leads to the release of greenhouse gases (GHGs) like N_2O , CH_4 , and CO_2 , exacerbating climate change [8].

In addition to understanding the potential environmental impacts of agricultural activities, a key aspect of sustainability is the use of appropriate indicators to assess and evaluate these effects. As mentioned, GHG emissions from fertilizers can serve as an objective indicator for assessing sustainability levels. Additionally, N use efficiency (NUE), related to soil N balance, is a widely used indicator to characterize the sustainability of N usage [9]. NUE as well as GHG emissions is closely related to the country's socio-economic conditions, a relationship that can be depicted using the environmental Kuznets curve (EKC) theory [10,11]. According to the theoretical EKC, pollutant emission increases with income and social development at the first stage, and then decreases with further socio-economic development [9]. Currently, most EKC analyses focused on pollution from the industrial and transportation, few studies focused on the agriculture sector [12]. Still, there have been attempts to apply the EKC framework in the agricultural domain. For example, Zhang et al. [9] pointed out that national economic and political conditions influenced the turning points of the EKC for NUE and global NUE should be increased from ~0.4 to ~0.7 to meet the demand for both food security and environmental protection in 2050. Yu et al. [13] found that the most of provinces in China followed the inverted U-shaped EKC model, and provincial turning points were closely related to local cash-crop ratio and economic conditions. However, these studies have only focused on a single indicator, and have overlooked the potential relationships between different indicators. More specifically, using different indicators for the same country could suggest that the country is at different stages of the EKC.

Due to the influence of physical geography and policies, the turning point of EKC varies significantly across different regions. National agriculture management strategies play an essential role in the farmland N flow, showing a complex relationship between agricultural productivity and environmental conservation [14]. In this research, we used the Food and Agriculture Organization of the United Nations (FAO) dataset to analyze NUE and farmland GHG emissions across 113 countries, to have a broad view of global agricultural sustainability. In this analysis, the environmental Kuznets curve theory was applied to explain the temporal change in NUE and GHG emissions. Furthermore, differences in EKC characteristics, such as turning points and lagging effects, along with national disparities, were analyzed to offer guidance for improving agricultural practices and achieving a sustainable future.

2. Materials and Methods

2.1. Agriculture Nitrogen Balance and Farmland Greenhouse Gas Emissions

Nitrogen use efficiency, defined as the ratio of farmland N_{output} to N_{input} , is a widely used indicator for sustainable agricultural development, shown as Equation (1).

$$\text{NUE} = \text{N}_{\text{output}} / \text{N}_{\text{input}} \quad (1)$$

where N_{input} represents the N inputs to the farmland, including the synthetic fertilizer, manure applied to soils, biological fixation, and atmospheric deposition, and N_{output} is the crop harvest N uptake (Figure 1). Thus, NUE reflects the proportion of nitrogen input that is converted into harvested crop nitrogen. In this study, the N balance components required for NUE calculation, including synthetic fertilizer application, manure applied

to soils, biological nitrogen fixation, atmospheric nitrogen deposition, and crop harvest nitrogen uptake, were directly obtained from the FAO database.

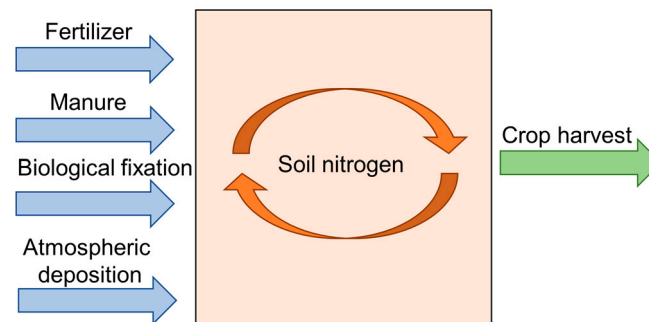


Figure 1. Schematic diagram of the nitrogen use efficiency calculation.

The farmland greenhouse gas emissions (in $\text{kg CO}_2\text{-e ha}^{-1}$) focus on the sections generated by farmland cultivation activities; the formula is shown as follows (Equation (2)).

$$\text{Farmland GHG emissions} = E1 + E2 + E3 \quad (2)$$

where the E1, E2, and E3 are GHG emissions from synthetic fertilizers, manure applied to soils, and rice cultivation (in $\text{kg CO}_2\text{-e ha}^{-1}$), respectively. In particular, GHG produced by rice cultivated (E3) refers to the CH_4 generated anaerobically from soil organic matter during rice cultivation, independent of fertilizer input. Different sources produce distinct primary GHG [8]. Specifically, E1 primarily emits N_2O , E3 releases CH_4 , and E2 discharges a combination of both N_2O and CH_4 . This paper does not account for greenhouse gas emissions from crop residue management, as most crop residues are used for composting, biofuel production, or animal feed, with emissions from these processes occurring outside of farmland [15]. However, in countries like China and India, emissions from crop residue burning are often excluded from estimates, potentially leading to an underestimation of total greenhouse gas emissions [16,17].

Different sources of GHG were calculated in terms of CO_2 equivalents per hectare. N balance, manure management and GHG data (1961–2018) are obtained from the Food and Agriculture Organization of the United Nations. Additionally, only countries with a cultivated land area greater than 10^6 ha were included in these studies, resulting in a total of 113 countries. These countries together accounted for more than 95% of global cultivated land area and farmland GHG emissions, indicating that the dataset captured the dominant share of global agricultural land use and related emissions. The social development data (GDP per capita) is obtained from World Development Index, World Bank.

2.2. Environmental Kuznets Curve Model Analysis

Environmental Kuznets curve analysis is an effective way to estimate sustainable development as it reflects the relationship between the degree of environmental degradation and social development [7,11]. Here, in this study, NUE and farmland GHG emissions are used as agricultural sustainability indicators, while GDP per capita, obtained from the World Bank, is used as a social development indicator. The following Equation (3) is used for fitting.

$$Y = A + Bx + Cx^2 \quad (3)$$

where Y is the NUE or farmland GHG emissions (in $\text{kg CO}_2\text{-e ha}^{-1}$) of different countries during 1961–2018, and x is the GDP per capita of different countries during 1961–2018, A, B, C are constants. It is important to note that, while both GHG and NUE are fitted with quadratic functions in this paper, their theoretical trends differ. GHG follows the traditional

environmental Kuznets curve, which forms an inverted U-shape. In contrast, studies show that NUE follows a U-shaped trend, as it reflects efficiency rather than pollution emissions [9]. This quadratic fitting procedure was applied at both the global and national scales, and the EKC turning points of NUE and farmland GHG emissions were identified from the fitted quadratic functions.

In this study, we specifically focused on the differences in the turning points of the EKC across different regions, as it indicates the transition of a country towards the stage of agricultural sustainable development.

3. Results

3.1. Global Historic Trend of Nitrogen Use Efficiency and Farmland Greenhouse Gas Emissions

At the global scale, NUE and farmland GHG emissions fit the EKC hypothesis well (Figure 1, $R^2 > 0.8$; $p < 0.01$). Both curves have crossed the turning points, indicating that the second stage of the EKC has been reached globally, in other words, moving towards sustainability. Although NUE and GHG may fluctuate from year to year due to climate conditions and policy changes, their overall trends remain clear and consistent. Global NUE declined and increased obviously, while farmland GHG emissions reached its highest point in the 2010s, and then had a slow downward trend. Global NUE declined from 0.55 in 1961 to 0.37 in 1988, and then increased to 0.45 in 2018, while GHG emissions increased from 584 to 939 kg CO₂-e ha⁻¹ and then with a slow downward trend (Figure 2). Although the decline in GHG emissions beyond the turning point is slow, the fact that this point has been reached underscores the difficulty of achieving great reductions in total emissions. The lowest value of global NUE occurred when gross domestic product (GDP) per capita reached ~\$8000 in the late 1980s, and the highest value of GHG emissions happened at ~\$13,000 GDP per capita.

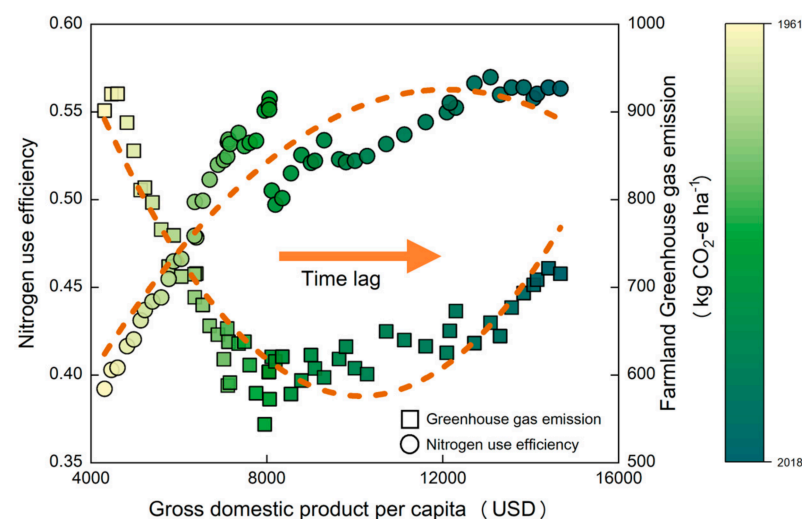


Figure 2. Global environmental Kuznets curves of nitrogen use efficiency and farmland greenhouse gas emissions. The dashed lines represent the quadratic function fitting curve.

The turning point is key to analyzing the EKC, as it plays an important role in estimating the different stages of development. In this study, though both farmland GHG emissions and NUE reached the second stage, the appearance of the two turning points could be different, with the GHG turning point lagging 3–5 years behind the NUE turning point (Figure 2). This result indicates that agriculture indicators may have different “sustainability shift points”, brought by different agricultural management strategies. For governments, crop yields and food security typically have a very high priority in national strategies [14]. Previous studies showed that about two-thirds of agriculture policies and

regulations incentivize the use of N to ensure crop yields and food supply [14]. Compared to GHG emissions, NUE is more directly related to crop yields, resulting in more sensitivity to food production increasing, leading to reaching the turning point earlier than farmland GHG emissions.

Certainly, the NUE has been accepted as an effective indicator to assess agriculture sustainability degree for meeting SDGs [9,18]. However, according to the lagging effect of the turning points mentioned, the idea of using only NUE as an agricultural sustainability indicator is challenged. An increase in NUE does not necessarily imply a reduction in total fertilizer input, nor does it guarantee a decrease in negative environmental impacts. In particular, when a country (such as the USA) reaches the turning point of NUE, with fertilizer input and GHG emissions still increasing, it is hard to say the country has reached the agricultural sustainability stage. Especially in light of future plans to control global warming to a 1.5 °C increase, focusing solely on NUE without incorporating an assessment of agricultural GHG emissions seems even more limiting [19].

3.2. Different Countries Are Experiencing Different Stages of Agricultural Development

Based on whether a turning point has been reached for NUE and GHG emissions, we classified the countries into four categories: Group 1 (both EKC of NUE and GHG emissions have reached turning points); Group 2 (only NUE reached the turning points); Group 3 (only GHG emissions reached the turning point); and Group 4 (neither NUE nor GHG reached the turning point).

Group 1 countries are primarily located in East Asia, Southeast Asia, Europe, Oceania, and Northern Africa, while Group 2 countries are concentrated mostly in the Americas. Group 3 includes fewer countries, scattered across the globe, and Group 4 is predominantly made up of nations in Central Asia, Northern Asia, and parts of Central and Southern Africa (Figure 3). There is a noticeable difference in the percentage of development of countries in these four groups. The percentage of developed countries generally decreases from Group 1 (41%) to Group 4 (4%). This finding verified that developed countries typically reach the turning point of the EKC earlier than developing countries. However, the GDP per capita at which different countries cross the EKC turning point varies, which may be influenced by management strategies, physical geography, and social culture of different countries [9]. Overall, the GDP per capita at the turning point for developing countries is much lower than that of developed countries. For example, the NUE turning point for the US and China was about GDP per capita \$30,000 and \$4200, respectively. This discrepancy highlights the potential late-mover advantages for developing countries within the realm of agriculture [7].

In Group 1, current agricultural management strategies seemed to work in these countries, while in other groups, local agricultural policies and regulations still need further improvement for sustainability. Despite having crossed both turning points, some Group 1 countries still have high GHG emissions. For instance, China and India's GHG emissions are 2464 and 1424 kg in kg CO₂-e ha⁻¹, respectively. This indicates that even within Group 1, there is great potential for emission reduction. In some developed countries (like the USA and Canada), which are clustered in Group 2, the policies for farmland GHG emissions mitigations are necessary and need to be further implemented. For example, less than 10% of farmers in the USA apply N best management strategies or technologies [20]. Still, some developed countries are classified into Groups 3 and 4. Yet, agriculture is not their primary industry. In these groups, the arable area of developed countries accounts for only 8.92% and 0.93% of the total arable area, respectively.

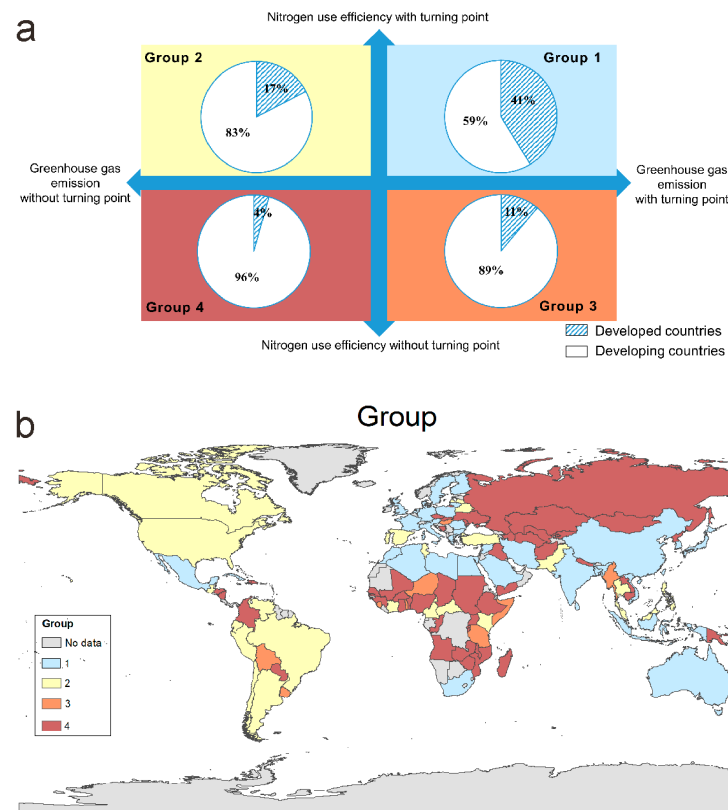


Figure 3. Grouping results and distribution. (a) Grouping of countries based on the presence or absence of an inflection point. The number of countries in each group is 34, 23, 9, and 47, respectively. (b) Grouping map.

3.3. Reducing Greenhouse Gas Emissions to Achieve Sustainable Agriculture While Enhancing Nitrogen Use Efficiency

The focus on agriculture has always been on yields, but in recent years there has been an increase in the environmental impacts of agricultural activities [14]. As one of the key indicators for achieving the SDGs, GHG emissions are primarily driven by industrial activities, which may lead to the neglect of agricultural GHG emissions [21]. Most countries tend to prioritize surpassing the NUE turning point over the GHG turning point. Compared to the downward trend in NUE, the reduction in agricultural GHG emissions is much slower (Figure 2). Therefore, we advocate for increased attention to the emissions of agricultural GHGs and further exploration of their reduction potential. In this section, six typical countries in different groups (Group 1: China and India; Group 2: Brazil and the USA; Group 3: Myanmar; Group 4: Russia) were selected to show the GHG emissions differentiation.

Compared to the NUE, variations in farmland GHG emissions are more pronounced across nations, with Asian countries such as China, India, and Myanmar generally exhibiting higher levels (Figure 4a). For example, in 2018, the GHG emissions from farmland in China and Myanmar were 2464 and 2838 kg CO₂-e ha⁻¹, respectively, compared to that of the USA, which was at 563 kg CO₂-e ha⁻¹.

In addition to differences in total farmland GHG emissions between countries, there is a significant variation in the contribution of each sector, including synthetic fertilizers (E1), manure application (E2), and rice cultivation (E3). The share of N₂O per unit area generated by fertilizers in farmland GHG is not much different in these countries, but given the difference in area of farmland, the impact of fertilizers in Asian countries could be greater. In Asian countries, particularly in China and India, the huge population has put enormous pressure on food production, leading to an increase in the use of synthetic

fertilizers to ensure food security and human livelihoods [7]. In these countries, there is great potential for GHG emissions reduction from the fertilizers sector through enhancing NUE and decreasing usage [7,9].

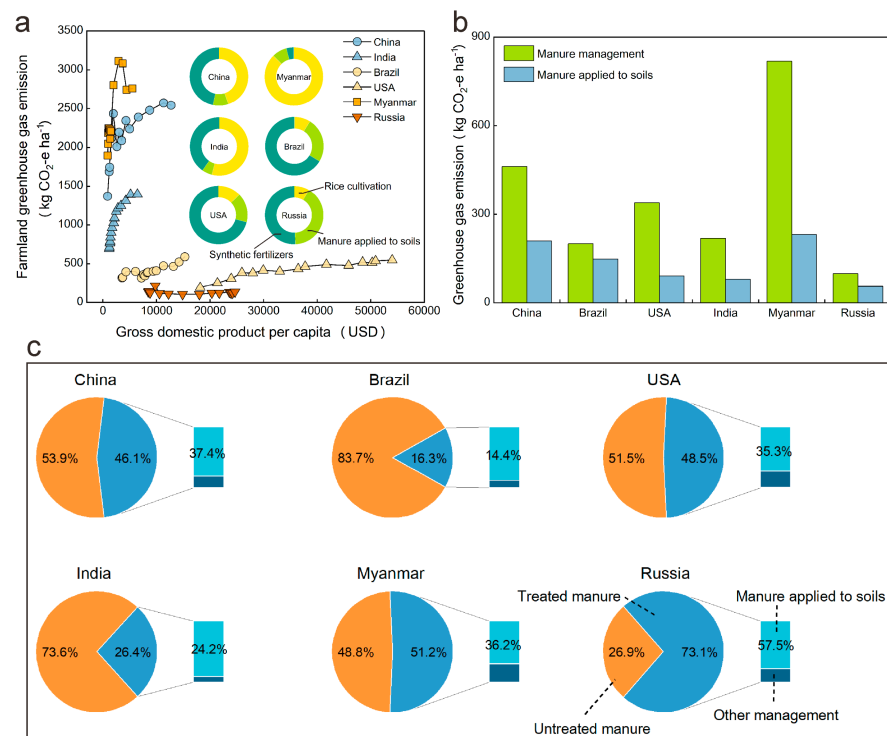


Figure 4. The potential of greenhouse gas emissions reduction. (a) Examples of historical trends of the relationship between gross domestic product per capita and farmland greenhouse gas emissions. Typical countries are from the mentioned groups, cyan represents Group 1 (China and India), deep yellow represents Group 2 (Brazil and USA), orange represents Group 3 (Myanmar), and brown represents Group 4 (Russia). The pie charts are the farmland greenhouse gas emissions composition of these countries in 2018. (b) Examples of greenhouse gas emissions from manure systems. (c) The distribution of manure management indicates that a large amount of manure is not fully reutilised.

GHG emissions from the E2 (manure applied to soils) sector have a higher proportion in Brazil and the USA, mainly due to well-developed and intensive livestock industries [22]. CH₄ and N₂O are major gases generated from microbial activities in the manure environment [23]. In non-Asian agricultural systems, particularly in the Americas and parts of Europe, mitigation priorities may differ from those in rice-dominated Asian countries. Large-scale dryland cropping systems and intensive livestock production make fertilizer optimization, manure storage, manure recycling, and feed-crop nutrient integration particularly important mitigation pathways. For example, in countries such as the USA and Brazil, where cropland systems are often dominated by maize, soybean, and pasture-associated production, reducing excess fertilizer inputs and improving manure management may provide greater climate benefits than water-saving rice irrigation [24]. Therefore, region-specific mitigation strategies should be developed according to the dominant agricultural structure and emission sources of each country [22]. Manure is a valuable resource; most of the reused manure is applied to soils as organic fertilizers, which has remarkable GHG emission reduction compared to other manure management (Figure 4b). In these countries, GHG emissions from manure applied to soils could be 210 kg CO₂-e ha⁻¹, while in other manure management, the GHG emissions could reach as high as 800 kg CO₂-e ha⁻¹ (Figure 4b). The management and reuse of manure also vary considerably at the national level, as shown in Figure 3b. While returning manure to soil can reduce GHG emissions,

less than half of the manure is reused, with even lower reuse rates in Brazil and India, at only 16.3% and 26.4%, respectively (Figure 4). Considering the proportion of manure reused and its mitigation for GHG emissions, the potential for reducing GHG emissions through manure management is huge, especially when advanced technologies (like adding loess, straw, biochar, and bentonite during the composting process) are applied [22,25].

For rice cultivation GHG emissions, the anaerobic environment created during rice cultivation provides the conditions for methane-producing microbial activities [26,27]. It should be noted that GHGs would be generated from underutilized N fertilizers through microbial decomposition both in paddy fields and drylands [28]. The E3 (rice cultivation) sector contributes more on farmland GHG emissions in China, India, and Myanmar. For Asian countries, rice is one of the main foods and they contributed nearly 90% of the global rice production in 2021. In the Americas, the main crops are soybeans and corn, cultivated in dryland areas that are less prone to the production of GHG generated in anaerobic conditions like methane [28]. Thus, improvement in rice cultivation, such as transferring from continuous flooding to alternate wetting and drying, intermittent irrigation, aerobic rice cultivation, sprinkler irrigation, or drip irrigation, could contribute to more sustainable agriculture by reducing water use, irrigation costs, and methane emissions generated under anaerobic conditions [29,30].

By implementing reasonable greenhouse gas mitigation measures in croplands, we can alleviate global warming while ensuring food security and enhancing NUE, towards a sustainable future.

4. Discussion

Our findings reveal that agricultural sustainability transitions are inherently multidimensional and asynchronous. While previous studies have frequently relied on a single indicator, particularly NUE, to evaluate agricultural sustainability, this study demonstrates that different sustainability indicators may exhibit distinct EKC turning points. The lag effect identified between NUE and GHG emissions indicates that improvements in nutrient-use efficiency alone cannot fully represent reductions in environmental pressure or progress toward climate goals. In many countries, particularly those experiencing rapid agricultural intensification, fertilizer-use efficiency has improved while total fertilizer consumption and agricultural GHG emissions continue to rise [9]. This discrepancy reflects the complex trade-offs among food security, agricultural productivity, and environmental protection [31,32].

The existence of lag effects also highlights the path dependency of agricultural systems. Nitrogen management strategies are often initially designed to stabilize crop production and ensure food supply, particularly in densely populated developing countries. As a result, policy interventions frequently prioritize productivity gains over emission reductions, which helps explain why the turning point for GHG emissions generally occurs later than that for NUE [14]. Similar lag phenomena have also been reported in other environmental systems, where improvements in efficiency indicators precede observable ecological benefits because of cumulative legacy effects, infrastructural inertia, and delayed policy responses.

The strong heterogeneity among countries further demonstrates that there is no universal pathway toward sustainable nitrogen management. Differences in cropping systems, livestock intensity, climate conditions, and governance capacity strongly influence both the magnitude and sources of agricultural GHG emissions [19]. Therefore, sustainability strategies should be adapted to regional agricultural structures and socio-economic contexts rather than relying on a single global framework.

The results also indicate that improving NUE alone may not necessarily reduce total environmental impacts. An increase in NUE can occur simultaneously with increasing fertilizer inputs and agricultural production expansion, especially in rapidly developing economies. Therefore, relying solely on NUE as a sustainability indicator may overestimate the environmental performance of agricultural systems. Integrating multiple indicators, including GHG emissions, nutrient surplus, and resource recycling efficiency, would provide a more comprehensive assessment of agricultural sustainability. Such multidimensional assessments are increasingly important under the dual pressures of global food security and climate mitigation. For instance, while methane mitigation from rice paddies is particularly relevant for Asian countries, non-Asian regions often require different priorities. In North and South America, large-scale dryland cropping and livestock systems suggest that improved fertilizer-use planning, manure recycling, and crop–livestock integration may be more important [22]. In Europe, where agricultural intensification has been accompanied by relatively stronger environmental regulations, further reductions may depend on precision nutrient management, circular manure use, and policies targeting both N surplus and agricultural GHG emissions [33].

Future nitrogen management should therefore move beyond improving NUE toward integrated management frameworks that simultaneously consider productivity, climate mitigation, and resource recycling. Existing strategies such as the “4Rs” nutrient stewardship framework (right source, right rate, right time, and right place) provide an important basis for improving fertilizer-use efficiency [28,34]. However, achieving deeper reductions in agricultural GHG emissions will require broader system-level transformations, including optimized manure recycling, low-emission livestock systems, water-saving rice cultivation practices, and improved coordination between crop and livestock production systems. In particular, the low proportion of manure reutilization identified in several countries indicates considerable untapped potential for circular nutrient management.

For countries dominated by rice cultivation, water-saving irrigation strategies could substantially reduce methane emissions while maintaining crop productivity [35,36]. In livestock-intensive regions, strengthening manure recycling systems may simultaneously reduce methane and nitrous oxide emissions while decreasing dependence on synthetic fertilizers, providing co-benefits for nutrient recycling and climate mitigation.

Socio-economic factors and governance capacity also play essential roles in determining agricultural sustainability transitions. Developed countries generally crossed EKC turning points earlier because of stronger technological capacity and environmental regulations, whereas developing countries may possess “late-mover advantages” by adopting advanced nitrogen management strategies without repeating environmentally intensive development pathways [7,9].

This study also has several limitations that should be acknowledged. First, the analysis was conducted at the national scale, which may obscure substantial regional heterogeneity within countries. Agricultural systems, climate conditions, and policy implementation can vary greatly across subnational regions, particularly in large countries such as China, India, and the United States. Second, farmland GHG emissions in this study focused primarily on synthetic fertilizer application, manure application, and rice cultivation, while emissions associated with crop residue burning and certain upstream agricultural processes were not fully incorporated because of data limitations. Although this study focused on farmland GHG emissions directly associated with cultivation activities, upstream emissions from synthetic nitrogen fertilizer production should also be considered when evaluating the full climate impact of agricultural nitrogen use. The Haber–Bosch process is energy-intensive and commonly relies on hydrogen derived from fossil fuel sources such as natural gas or coal, leading to additional and spatially localized GHG emissions during fertilizer manu-

facturing [37]. Therefore, our estimates do not capture the full life-cycle climate burden of synthetic fertilizer use, and future assessments should integrate both field-level emissions and upstream industrial emissions to better evaluate the climate consequences of nitrogen management [38]. Third, although the EKC framework provides a useful conceptual approach for evaluating sustainability transitions, agricultural development trajectories are influenced by multiple interacting socio-economic, technological, and political drivers that may not always follow idealized quadratic relationships.

Despite these limitations, this study provides a global perspective on the asynchronous transition between NUE and agricultural GHGs. The results highlight that improving nutrient efficiency does not automatically guarantee climate benefits and that sustainable agricultural development requires coordinated management across multiple environmental dimensions. As food demand continues to rise under climate change and population growth, integrating nitrogen management with climate mitigation strategies will become increasingly critical for achieving long-term agricultural sustainability.

5. Conclusions

Using data from 113 countries during 1961–2018, this study demonstrated that both NUE and GHG emissions generally follow environmental Kuznets curve relationships with economic development, but their turning points occur asynchronously, with the turning point for NUE appearing earlier than that for farmland GHG emissions. This lag effect indicates that improvements in nutrient-use efficiency do not necessarily lead to immediate reductions in agricultural environmental impacts, highlighting the limitations of relying solely on NUE to evaluate agricultural sustainability. Different countries are currently experiencing distinct stages of sustainability transition because of differences in agricultural structure, socio-economic development, and environmental governance, with rice-dominated countries showing large mitigation potential through fertilizer optimization and water-saving irrigation, while livestock-intensive countries possess substantial opportunities through improved manure management and nutrient recycling. Overall, sustainable nitrogen management requires integrated strategies that simultaneously address food security, nutrient efficiency, and climate mitigation, and future agricultural policies should adopt multidimensional sustainability frameworks that combine productivity goals with broader environmental outcomes.

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Data Availability Statement: The data presented in this study are derived from publicly available resources. The FAO data can be accessed at <https://www.fao.org/faostat/en/#home> (accessed on 20 May 2026), and the World Bank data can be accessed at <https://data.worldbank.org/> (accessed on 20 May 2026).

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

N	Nitrogen
SDG	Sustainable Development Goal
GHG	Greenhouse Gas
NUE	Nitrogen use efficiency
EKC	environmental Kuznets curve
FAO	Food and Agriculture Organization of the United Nations

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