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Research Article

# Opportunity and shift of nitrogen use in China

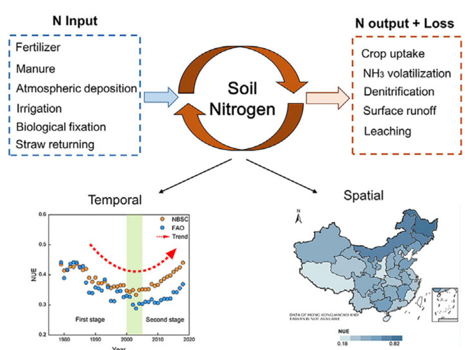
Wangzheng Shen[a,b,1], Jing He[c,d,e,1], Sisi Li[a,b], Yanhua Zhuang[a,b], Hongyuan Wang[f], Hongbin Liu[f,*], Liang Zhang[a,b,*], Andreas Kappler[g]

[a] Hubei Provincial Engineering Research Center of Non-Point Source Pollution Control, Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences, Wuhan 430077, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] School of Environmental Studies, China University of Geosciences (Wuhan), Wuhan 430078, China
[d] State Environmental Protection Key Laboratory of Source Apportionment and Control of Aquatic Pollution, Ministry of Ecology and Environment of the People's Republic of China, Wuhan 430078, China
[e] Hubei Key Laboratory of Yangtze River Basin Environmental Aquatic Science, Wuhan 430078, China
[f] Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China
[g] Geomicrobiology Group, Center for Applied Geosciences (ZAG), University of Tuebingen, Tuebingen D-72076, Germany

## HIGHLIGHTS

- National NUE has crossed the turning point of the environmental Kuznets curve.
- Socioeconomic development dominated the changes in N use patterns in China.
- China might take 20–25 years to achieve the targeted NUE of 0.6.

## GRAPHICAL ABSTRACT

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## ABSTRACT

It is never an easy task for China to feed 1.4 billion people with only 7% of the world's arable land. With nearly 30% of the world's nitrogen (N) fertilizer applied, China achieves high crop yields while facing N pollution resulting from excessive N input. Here, we calculate the farmland N budget on the national and regional scales. The N use efficiency (NUE) in China increased by 28.0% during 2005–2018. This improvement is due to the reduction in fertilization and the improvement of crop management. The fragmented farmland is changing to large-scale farmland with the increase in cultivated land area per rural population and the development of agricultural mechanization. This opportunity brings more possibilities for precision farmland management, thus further improving NUE. The goal of an NUE of 0.6 may be achieved in the 2040s based on the current development trend. This striking N use shift in China has important implications for other developing countries.

## 1. Introduction

The nitrogen (N) supply sustains and increases crop yields for feeding the global population (Robertson and Vitousek, 2009; Canfield et al., 2010). In the early 20th century, the discovery of the Haber-Bosch process enabled people to synthesize $NH_3$ much more effectively than natural processes, which greatly increased the world's food production

* Corresponding authors.
*E-mail addresses:* liuhongbin@caas.cn (H. Liu), lzhang@apm.ac.cn (L. Zhang).
[1] These authors contributed equally to this work.

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(Cherkasov et al., 2015). The benefits that humans have gained are enormous, but they have come at an enormous cost to both the environment and energy resources (Li et al., 2023; Shen et al., 2021). Excessive N input in farmland has resulted in a series of environmental consequences, including air pollution, greenhouse gas emissions, biodiversity loss, surface water eutrophication, and groundwater nitrate pollution in many countries (Scanlon et al., 2007; Tilman et al., 2011; Glibert et al., 2014; Shen et al., 2023a). Furthermore, the long-term N accumulated from agricultural activities can have negative impacts on water bodies for decades, greatly hampering efforts to improve environmental quality (Van Meter et al., 2018; Basu et al., 2022).

Faced with the growing populations of developing countries, there are serious challenges in maintaining high crop yields while reducing the environmental impact of excessive N input (FAO, 2018). As the world's largest N synthetic fertilizer application country, China feeds 20% of the global population with only 7% of the world's cultivated land and applies nearly 30% of the world's synthetic N fertilizer (Table S1 and Table S2) (Gu et al., 2015). In recent years, the Chinese government has made great efforts to reduce the negative environmental impact of excessive N input, including encouraging the use of organic fertilizers and promoting straw return. The results of these measures are remarkable: the synthetic N fertilizer input in China reached its peak in the 2010s, and the utilization rate of organic fertilizers increased. Currently, most existing research has assessed the farmland N budget on a national scale (Zhang et al., 2015; Bouwman et al., 2017); however, farmland spans temperate, subtropical, and tropical climates, and different regions have great spatial heterogeneity in China. These vast differences in physical geography and social development have led to regional variations in sustainable agricultural development, but few studies have taken into account this spatial heterogeneity within China. Therefore, it is crucial to re-examine the changes in N cycling brought about by socioeconomic development and geographical differences.

In response to the great spatial heterogeneity within China, different regions require different approaches to agricultural N management. Here, we assessed the N budget of farmland in China from 2005 to 2018 at the regional scale and analyzed the shifts in N use during this period. The specific objectives of this study include: (1) quantifying N use and loss in different regions of China, (2) analyzing the spatial-temporal heterogeneity of the N budget in China and exploring its potential driving force, (3) summarizing the shift in N use in Chinese farming systems and future opportunities.

## 2. Materials and methods

### *2.1. Data collection*

The study area covered the whole area of China's mainland. Taiwan, Hong Kong, and Macau were not included due to the lack of data. Here, we built two databases to calculate the N budget: the basic information database and the coefficients database. The basic information database mainly includes population, crop harvest area, crop yield, fertilizer, livestock amounts, and precipitation. Notably, all cultivated areas used in this paper were sown areas. These data were taken from the National Bureau of Statistics of China (NBSC) and the Food and Agriculture Organization of the United Nations (FAO) database. The NBSC is the most comprehensive data of China's provincial data, and the comparison of different data sources is shown in the Results section. The coefficients were used for the calculation of N fluxes, such as the biological N fixation rate. These coefficients mainly came from field experiments and observation data in China. We extracted these data from the literature to establish a comprehensive parameter database. Limited by data sources, the time series of provincial data is 2005–2018, and national data is 1979–2018. Based on the geographical features and administrative divisions of China, we divided China's mainland into seven regions: North, East, Northeast, Central South, Southwest, Northwest, and Qingzang Plateau. The regional-scale assessment results were aggregated based on provincial results. The Northeast region includes Heilongjiang, Jilin, and Liaoning; the North region includes Beijing, Tianjin, Hebei, Inner Mongolia, and Shanxi; the East region includes Shandong, Jiangsu, Zhejiang, Fujian, and Jiangxi, the Central South region includes Henan, Hubei, Hunan, Guangxi, and Guangdong; the Southwest region includes Sichuan, Yunnan, Chongqing, and Guizhou; the Northwest region includes Shaanxi, Ningxia, Gansu, and Xinjiang; the Qingzang Plateau includes Xizang and Qinghai.

### *2.2. Model description*

We used the N mass balance to calculate and quantify the N inputs and outputs of China's farmland during 2005–2018. The basic balance formula is as follows:

$$\text{Input} = \text{Crop uptake} + \text{Loss} + \text{Surplus} \tag{1}$$

N inputs to the farmland system include synthetic fertilizer, manure (including livestock and human manure), biological N fixation (including symbiotic and non-symbiotic N fixation), atmospheric deposition (including dry and wet deposition), irrigation and straw return. N loss includes surface runoff, leaching, and gas emission (including $NH_3$, $N_2$, $N_2O$, and NO). Some minor N budget terms are neglected, such as N loss by wind erosion and input in seeds.

The input of synthetic fertilizers includes N fertilizer and compound fertilizers, with the N content of compound fertilizer calculated as 30% (Sun et al., 2020). Manure returned to the field, also known as organic fertilizer, was divided into two parts of the calculation: livestock manure and human manure returned to the field. Regional livestock manure application is derived from the national total amount (available in the FAO database) and then downscaled to the provincial scale based on the livestock number in each area (Shen et al., 2023b). Human manure was calculated based on the rural population and rate of manure returning to fields. To ensure accuracy, we also took into account the popularization rate of harmless toilets in different areas, as rural sewage treatment facilities have a significant impact on per-capita export coefficients (Tong et al., 2020). Biological N fixation was determined based on the fixation rates of different crop types. In this study, crops were categorized into legumes, rice, and others, with each category having distinct N fixation rates (Gu et al., 2015). Atmospheric N deposition was calculated based on the atmospheric deposition coefficient, which included both dry and wet deposition (Lu and Tian, 2007; Liu et al., 2013). This coefficient considered variations across different regions and times. The N input of irrigation water was estimated based on the irrigation water volume and the average irrigation water N concentration. Returning straw to the field is a method of reusing crop straw resources. It was estimated based on the amount of N resources in the straw and the rate at which it was returned to the field.

For crop uptake, we categorized crops into 11 groups: rice, wheat, corn, other cereals, legumes, tuberous crops, oil crops, sugar crops, vegetables, fruits, and other crops. For each type of crop, two parts were used to calculate crop harvest N: seed and straw. Seed N was estimated based on crop yields and different crop N contents, while straw N was estimated based on crop yields, N content in straw, and the ratio of straw to crop grain. The loss of gaseous N from farmland was estimated based on the emission factor, which considered the differences between the northern and southern of China and the different types of farmland (upland and paddy fields). The emission factors used in this study are shown in Table S3. Farmland surface runoff and leaching were estimated through the surface runoff/leaching coefficient and crop harvest area. Three empirical models were built to calculate the surface runoff/leaching coefficient of each province in different years. These models were constructed using the surface runoff/leaching coefficient of each province in the first Chinese pollution source census and the provinces' annual precipitation in 2007 (the year of the first Chinese pollution source census) (Tong et al., 2020). Since agricultural non-point source pollution is driven by precipitation (Shen et al., 2020), employing these models to estimate N loss effectively captures the effects of annual precipitation variations on N loss. The empirical models are shown as follows:

$$SR_{paddy} = 0.96 \times P_r - 1.16 \quad (2)$$

$$SR_{upland} = 0.96 \times P_r + 2.20 \quad (3)$$

$$L_{upland} = 0.60 \times P_r + 1.97 \quad (4)$$

where $SR_{paddy}$ represents the annual surface runoff coefficient of paddy fields in each province (kg•ha$^{-1}$•yr$^{-1}$), $P_r$ represents the annual precipitation in each province (m), $SR_{upland}$ represents the annual surface runoff coefficient of uplands in each province (kg•ha$^{-1}$•yr$^{-1}$), and $L_{upland}$ represents the annual leaching coefficient of uplands in each province (kg•ha$^{-1}$•yr$^{-1}$). The leaching of paddy fields was neglected in this study. All three models are significant ($P<0.01$), and the Pearson's correlation coefficients of these models are 0.88, 0.70 and 0.73, respectively.

### 2.3. Index construction

To assess farmland N utilization and related environmental impacts in China, we constructed three indexes: N surplus rate (NSR), N use efficiency (NUE), and N loss rate (NLR). The calculation methods are shown as follows:

$$NSR = Surplus/Input \quad (5)$$

$$NUE = Cropharvest/Input \quad (6)$$

$$NLR = (Gasloss + Surfacerunoff + Leaching)/Input \quad (7)$$

NSR, NUE, and NLR represent different paths of farmland N. Indeed, NUE has been proposed as an indicator to assess progress toward the Sustainable Development Goals (Zhang et al., 2015), while NSR and NLR indicate soil N surplus and direct environmental impact.

## 3. Results

### 3.1. General budget and spatial heterogeneity

At the national scale, the N input was 41.4 Gg in 2005, and then slightly increased to 45.4 Gg in 2014, after which the N input began to decrease (Fig. 1a). Our results showed that in 2018, synthetic fertilizer was the major N input in farmland input, accounting for more than 60% of the total input at the national scale, while manure, irrigation, atmospheric deposition, biological N fixation and straw return accounted for 14.9%, 0.18%, 6.1%, 9.5%, and 4.7%, respectively. Under different N input, crop uptake showed a continuous increase, rising from 14.6 Gg in 2005 to 19.1 Gg in 2018 (Fig. 1b). Meanwhile, the total N loss fluctuated between 12.9 Gg and 14.0 Gg. Crop harvest, $NH_3$, $NO_x$, $N_2$, surface runoff, and leaching accounted for 59.67 %, 17.7 %, 1.23 %, 14.46 %, 4.02 %, and 2.92 % of the N output, respectively.

Different regions in China showed obvious spatial heterogeneity in the farmland N budget. For instance, N input in East China, the most developed region, showed a significant decline during 2005–2018 ($P<0.01$), while the peak values of N input in the North, Northeast, Central South, Southwest, and Northwest China appeared in 2010, 2014, 2012, 2014 and 2015, respectively (Fig. S1). Except for East China and the Qingzang Plateau, N output in other regions increased significantly due to the increase in crop yields ($P<0.01$, Fig. S1).

Due to the spatial heterogeneity in climate and soil, there are great differences in crop selection in different regions (Fig. 2a). Northeast, Central South, East, and Southwest China are the main rice-producing areas (paddy fields), while Northwest, North, East and Central South China are the main maize rice-producing areas (upland) in China. This variation leads to different N loss pathways in different regions. Denitrification is more likely to occur in anoxic environments, and ammonia volatilization is the main path of N loss in uplands (Ju et al., 2009). Ammonia volatilization was the greatest N loss path (more than 60%) in North and Northwest China, while denitrification was the dominant one in East and Central South China in 2018 (Fig. 2b). Compared to the gas loss, the proportion of N loss to the water bodies (surface runoff and leaching) was smaller. This proportion was greatest in Southwest and Northeast China among all regions, accounting for 19.7% and 18.7% of the total N loss in 2018, respectively.

Notably, the uncertainties in the estimation of the N loss amount can be great. Neither the denitrification process nor non-point source pollution is well constrained on a regional scale anywhere in the world (Gu et al., 2015; Duan et al., 2023; Shen et al., 2020). Nevertheless, the emission factor used in this study considered the differences in different crop systems and different regions; therefore, the proportion of N loss paths could still reflect the spatial heterogeneity.

### 3.2. National temporal trend

The national NUE curve showed a U-shape during 1979–2018 (Fig. 3a). The national NUE in 1979 was 0.44 and continued to decrease

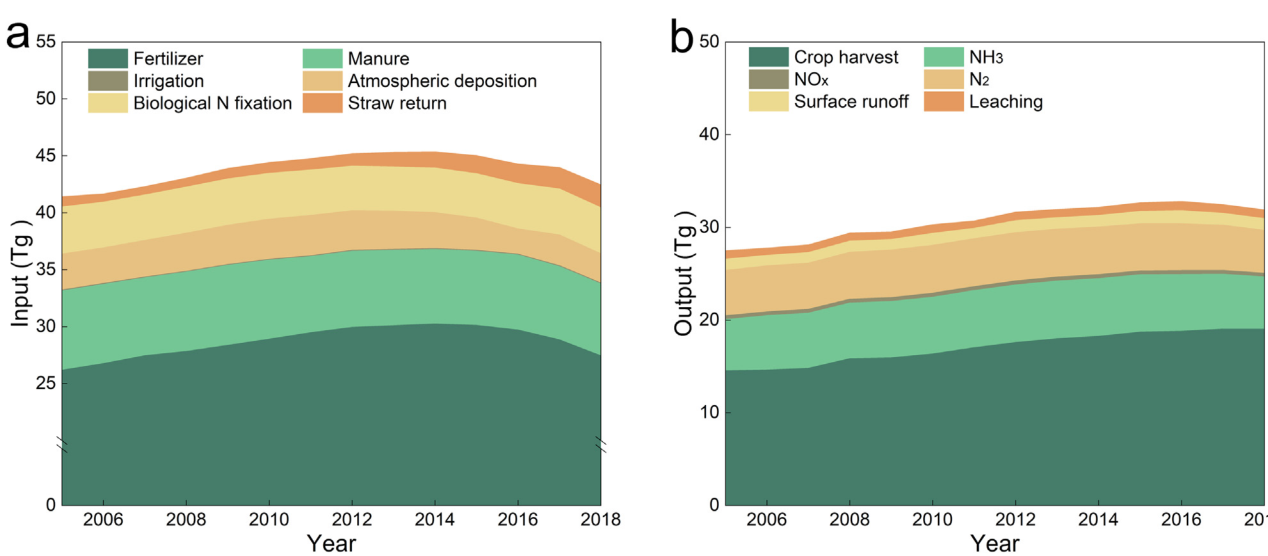


**Fig. 1.** National farmland nitrogen (N) input (a) and output (b) in China during 2005–2018.

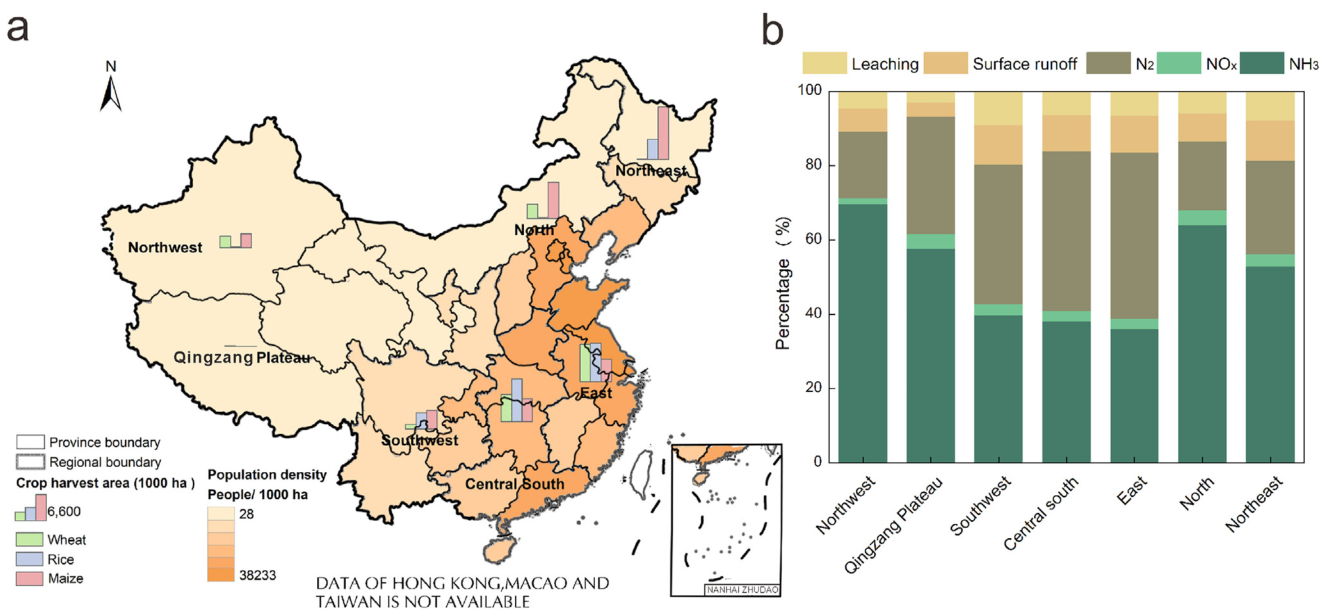


**Fig. 2.** Major crop harvest distribution in China and regional nitrogen loss pathway pattern. (a) Distribution, crop harvest area and population density (province-scale) in different regions of China in 2018. The histogram shows the crop harvest area of wheat, rice and maize. All histograms have the same axis. The map shows the population density of provinces. (b) The proportion of nitrogen loss paths in seven regions of China in 2018.

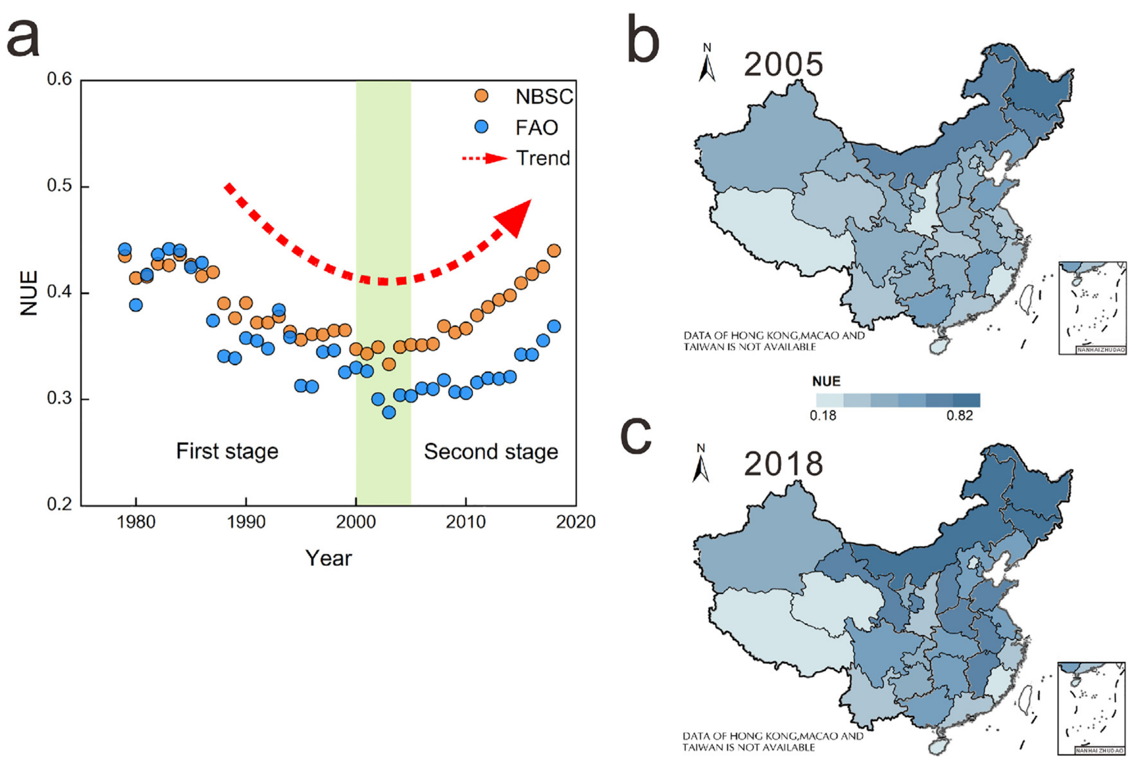


**Fig. 3.** National and regional nitrogen use efficiency (NUE). (a) National NUE during 1979–2018. The brown dots (1979–2018) represent the result of this study based on the National Bureau of Statistics of China (NBSC), the blue dots (1979–2018) represent the result of this study based on Food and Agriculture Organization of the United Nations (FAO). (b) NUE in different provinces in 2005. (c) NUE in different provinces in 2018.

until the beginning of the 21st century. The lowest value of China's NUE was 0.33 in 2003, when the gross domestic product (GDP) per capita was 1,090 USD. After crossing the lowest value, the NUE continued to increase and reached 0.44 in 2018. In addition, we also compared the impact of different data sources on the NUE calculation results. While specific values may vary between data sources (NBSC and FAO) they share similar trends (Fig. 3a).

### 3.3. Regional temporal trend

Our results revealed great spatial heterogeneity in China's N farmland budget. NUE and NSR exhibited mirrored changes, with regions exhibiting high NUE tending to have low NSR (Fig. 4, Fig. S2). Northeast China had the highest NUE (0.65) and the lowest NSR (0.11) among the seven regions in 2018. The fertilizer input in Northeast China was

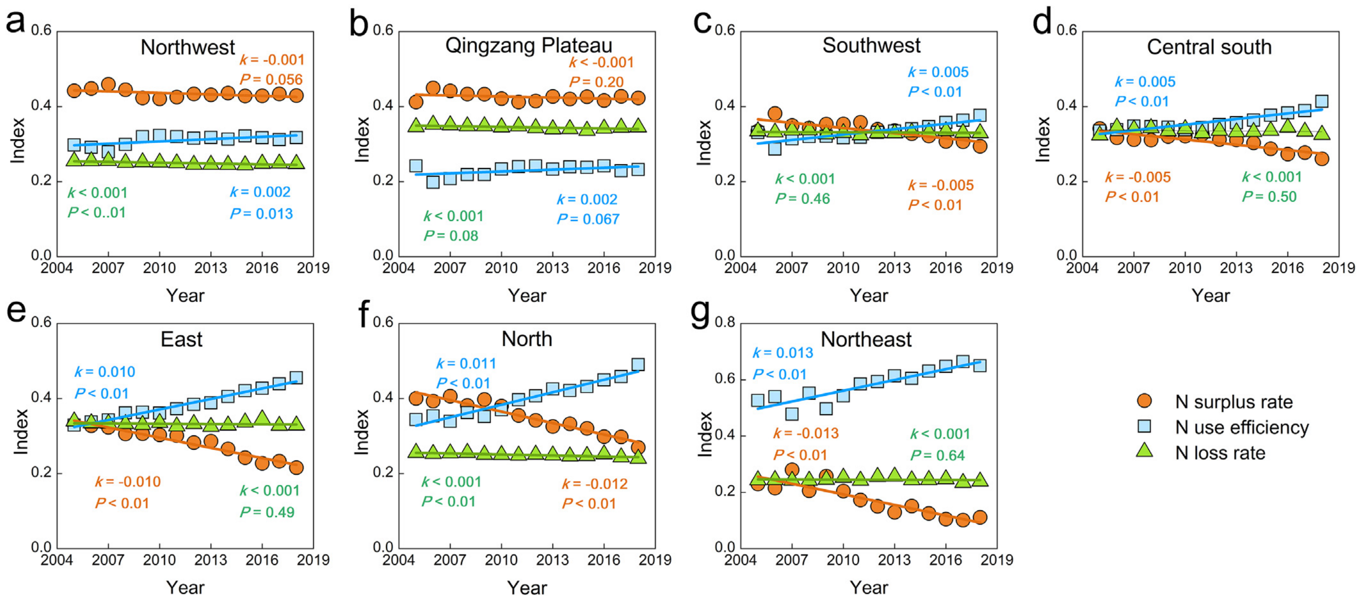


**Fig. 4.** Temporal changes of nitrogen surplus rate (NSR), nitrogen use efficiency (NUE) and nitrogen loss rate (NLR) in different regions during 2005–2018. (a) Northwest China; (b) Qingzang Plateau; (c) Southwest China; (d) Central South China; (e) East China; (f) North China; (g) Northeast China. '*k*' represents the slope.

relatively low (30.9% lower than the national average in 2018), but high crop yields have still been achieved. Contrary to Northeast China, the Qingzang Plateau area had the lowest NUE (0.23) and the highest NSR (0.42) with low fertilizer input. In addition, the NSR in Northwest China was also relatively high, especially in Xinjiang (Fig. S2). On the temporal scale, except for Northwest China and the Qingzang Plateau, NUE showed a significant increase during 2005–2018 ($P$<0.01), while NSR has shown a significant decline ($P$<0.01, Fig. 4). Furthermore, NUE values in North, East and Northeast China increased by more than 40 %, while those in Southwest China increased by only 20% during 2005–2018. At the same time, NSR showed an opposite pattern (Fig. 4). For N loss, the average NLR in China was 0.30, and there was no significant trend during 2005–2018 ($P$>0.01). The NLR exhibited marked regional disparities, with East China having the highest NLR and Northeast China the lowest among all regions.

## 4. Discussion

### 4.1. *Comparison of N budget: China and the world*

Despite the increasing trend, NUE in China is still much lower than that in developed countries (Zhang et al., 2015; Bouwman et al., 2017). As a leading global consumer of fertilizers, China's farmland N budget follows a "high input-high yield" pattern. China's N fertilizer input, measured in kg per hectare, exceeds the global average by 136.7%. Meanwhile, the crop yields (kg•ha$^{-1}$) of wheat, rice, and maize were higher than the world average by 58.0%, 52.5%, and 6.8%, respectively (Fig. 5). Despite the enormous input of fertilizer and high crop yield, there is still a gap between China and the countries with the highest crop yield in the world. The mean yields of wheat in New Zealand, rice in Australia, and maize in Israel were 65.4%, 47.8%, and 270.8% higher

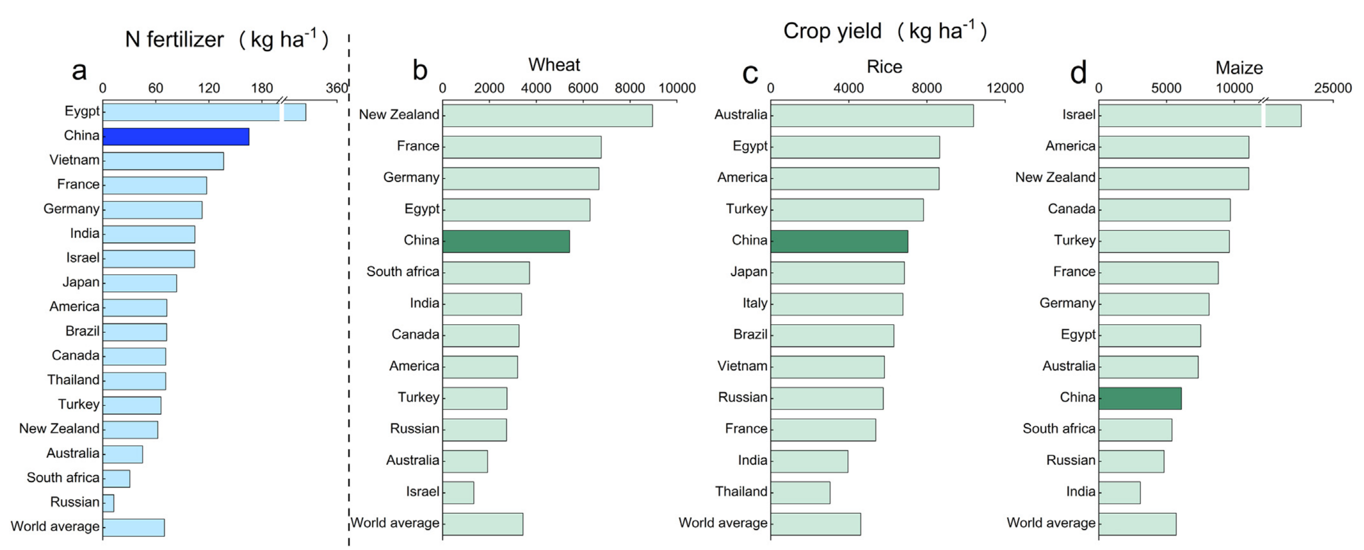


**Fig. 5.** Comparison of fertilizer input and crop yield among different countries. Fertilizer input (a), wheat yield (b), rice yield (c) and maize yield (d) for selected countries and regions in 2018. Values for China are highlighted by dark color.

than the mean yield in China for 2018, respectively. Contrary to China, these high-yield countries do not rely on the high input of fertilizer. Along with China's 'high input-high yield' pattern comes an enormous emission of pollutants.

### 4.2. National N use changes through the lens of the environmental Kuznets curve

According to the theoretical curve of the environmental Kuznets curve (EKC), in the first stage, NUE will decrease with economic development due to the expansion of food security, and then increase with further economic growth, eventually reaching the theoretical limit of the crop system (Zhang et al., 2015; Shen et al., 2023b). The temporal trend of national NUE from 1979 to 2018 fits the hypothesis of the EKC well. Furthermore, unlike a previous study that considered China to be in the first stage of the EKC (Zhang et al., 2015), our analysis indicated that China crossed the turning point in the early 21st century. Here, policies in China are considered a major driving force for NUE changes.

In 1978, China initiated an ambitious program of economic reform and opening up, and the household contract responsibility system (HCRS) began to be implemented in rural areas. The HCRS allocates farmland equally to rural householders, which greatly arouses farmers' enthusiasm for agricultural production and gives farmers more independent choices (Ju et al., 2016; Wu et al., 2018). Furthermore, thanks to the national macro regulation that guarantees a stable supply and fertilizer subsidy policies, the fertilizer price in China is lower than that in the global market. Although this policy has helped farmers to improve their incomes, it has also created a strong incentive for them to invest in fertilizers to obtain higher yields, rather than adopting more advanced and efficient agronomic practices (Li et al., 2013; Zhang et al., 2015). The rapid growth of fertilizer input has led to a downward trend in NUE. The massive application of fertilizer has brought serious environmental problems to China, including water eutrophication, air pollution, and biodiversity loss (Le et al., 2010; Gu et al., 2014; Huang et al., 2014; Shen et al., 2023a). At this stage, China sacrificed the environment to ensure food production. As environmental problems become increasingly prominent, the Chinese government pays more attention to the solutions for environmental problems. In 1998, the Chinese government established the State Environmental Protection Administration, and in 2008, it reformed the Ministry of Environmental Protection. In addition, the successful bid for the 2008 Beijing Olympic Games has also promoted the awakening of environmental awareness among Chinese people. Driven by these factors, China crossed the turning point of NUE in the early 21st century, and NUE has continued to rise since then (Fig. 3a). Among all regions, North, East and Northeast China contributed the most to the national NUE, crossing the turning point, as they have a rapid growth rate (Fig. 4). In general, aligned with previous studies, agricultural policies, especially fertilizer-related policies, were identified as the key driver of NUE changes in China (Yan et al., 2022; Gu et al., 2015). In the early period, excessive fertilizer inputs in pursuit of crop yields led to a decrease in NUE, and then NUE began to increase as a result of the prominence given to environmental protection and greater emphasis on sustainable agricultural development.

Compared to the developed countries, China's NUE turning point occurred later. For instance, Germany and France saw their turning points in the 1980s, and the United States reached the turning point in the 1990s (Zhang et al., 2015). At the same time, when China reached its turning point, per capita GDP was much lower. The United States reached the turning point at 40,000 USD, while Germany and France did so at 25,000 USD. China, however, reached the turning point of the EKC with a per capita GDP of just 1,090 USD. This result suggests that, compared to developed countries, China has a late-mover advantage in the agricultural field. Moreover, it underscores that regions yet to reach a turning point in NUE could potentially benefit from insights drawn from China's experience.

### 4.3. Driving force of the regional N use shift

The spatial-temporal heterogeneity in the N use pattern is determined by both physical geography and socioeconomic factors. Overall, fertilizer input is closely related to soil nutrition, and poor soils rely more on fertilizers to ensure high crop yields. The black soil in Northeast China has a very high organic carbon (SOC) content, which can help achieve high crop yields with low fertilizer input (Fig. S1) (Canfield et al., 2010; Ren et al., 2020). In contrast, the fertilizer input in Xinjiang increased by 49.5% during 2005–2015 and peaked of 242.0 kg•ha$^{-1}$ in 2015 (NBSC, 2018). The rapid growth of fertilizer use in Xinjiang is accompanied by an increase in cropland (increased by 162.7% during 2005–2018), and this newly increased cropland was mainly transformed from the Gobi Desert (Du et al., 2015). The poor soil (desert soil) makes Xinjiang's crop production depend heavily on fertilizer input. For temporal trends, in most regions of China, the SOC improved between 1980 and 2011 (Zhao et al., 2018), which promoted an increase in NUE and a decrease in NSR. SOC sequestration is largely attributed to straw return and organic fertilizer application, which are driven by economics and policy (Zhao et al., 2018).

Socioeconomic development promotes the adoption of advanced crop management measures, which is considered the key to crossing the turning point of the EKC (Zhang et al., 2015; Yan et al., 2022). From 2005 to 2018, China experienced a significant loss of its rural population, resulting in a drop in the proportion of the rural population from 56.4% to 39.9% of the total population. However, to a certain extent, this has promoted the improvement of crop management levels in China (Wang et al., 2021; Shen et al., 2023b). With the reduction in the rural population, the cultivated land area per rural population increased by nearly 40% during 2005–2018 (Fig. 6d). This expansion of farmland scale makes intensive production more feasible (Ju et al., 2016; Wu et al., 2018). In this paper, we used the mechanical sowing ratio and mechanical harvest ratio to describe the shift in agricultural management in China. For spatial differences, northeast, north, and east China have a high mechanical harvest ratio (over 65%), while southwest China has a low mechanical harvest ratio (lower than 20%). The topography of the region may have influenced these results, as mountainous areas in the southwest limit the use of agricultural machinery (Fig. 6). Regarding the temporal trend, the mechanized sowing ratio and mechanical harvest ratio increased 88.8% and 175.2% during 2005–2018, respectively. Our results showed that the mechanical sowing ratio and mechanical harvest ratio were significantly correlated with NUE and NSR ($P$<0.01, Figs. 6b, 6c). This result is consistent with the conclusions of previous studies that mechanical tillage can improve soil structure and increase crop yields (Mu et al., 2016; Sang et al., 2016; Zhai et al., 2019). We used a simple linear model to predict the future trends of NUE and NSR relative to the level of mechanization in China (Fig. 5). To meet the set NUE goal of 0.6, which considers global food demand and N surplus limits (Zhang et al., 2015), the mechanical harvest ratio needs to reach over 90%, which may take China 20–25 years to achieve based on the current trend.

### 4.4. Opportunities and challenges for future N use in China

Mechanized and large-scale agricultural management modes are more conducive to the implementation of crop management measures. Numerous field experiments and the temporal trends of NSR and NUE have shown great potential for improving NUE through crop management measures (Ju et al., 2009; Zhang et al., 2016; Cui et al., 2018; Chen et al., 2021). Different crop management measures have different applicable conditions. For instance, straw return can increase SOC, but it can also increase greenhouse gas emissions, especially in paddy fields and vegetable fields (Chen et al., 2013; Shang et al., 2021). The implementation of crop management measures requires comprehensive consideration of the impact on crop yields, environmental consequences,

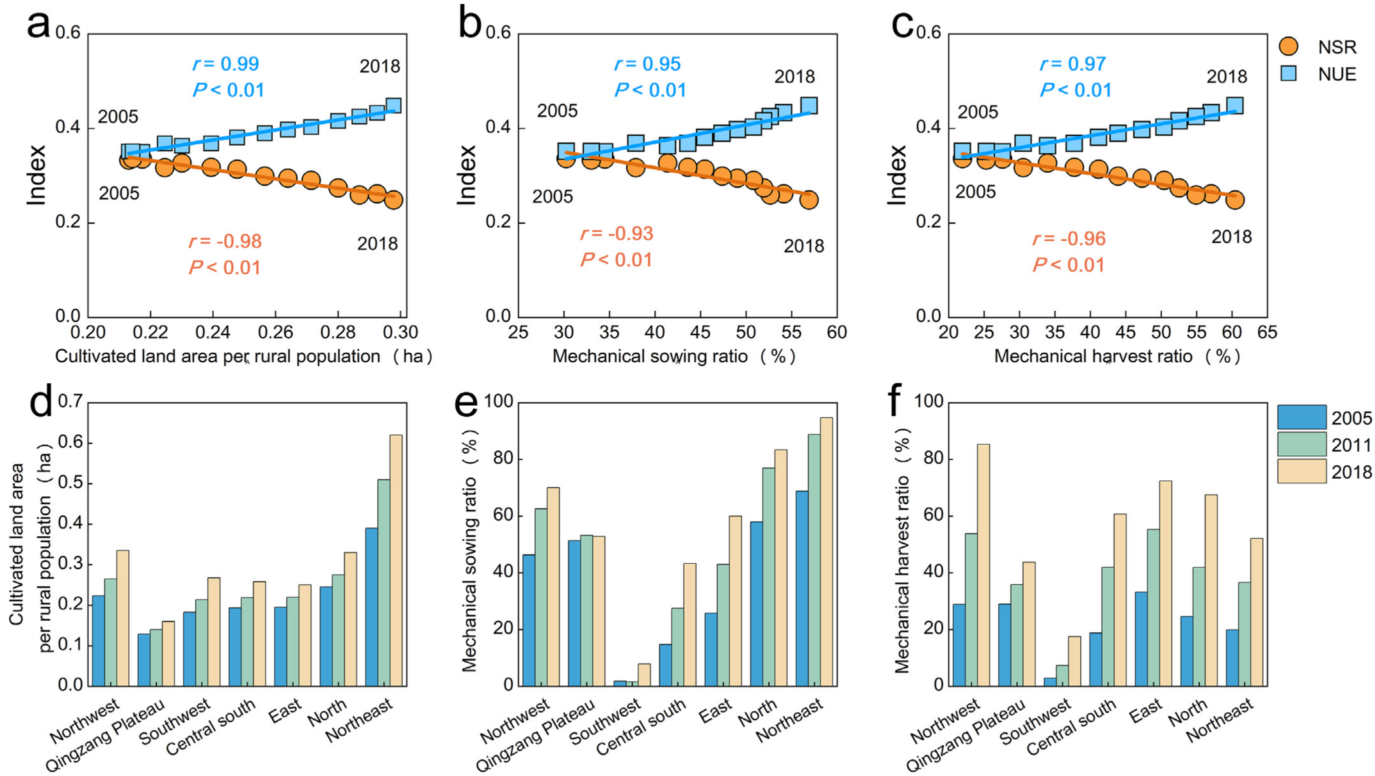


**Fig. 6.** Changes of cultivated land per rural population (ha), mechanical sowing ratio (%) and mechanical harvest ratio (%) in China during 2005–2018. The correlation between cultivated land per rural population (a), mechanical sowing ratio (b), mechanical harvest ratio (c) with nitrogen use efficiency (NUE) and nitrogen surplus rate (NSR). '*r*' represents the Pearson correlation coefficient. The cultivated land per rural population (d), mechanical sowing ratio (e), mechanical harvest ratio (f) in different regions of China in 2005, 2011 and 2018.

and actual social development, among which crop yields have the highest rank.

Over the past decades, China has made great progress in N utilization, especially after 2003, achieving increased NUE while feeding hundreds of millions of people. This progress has greatly contributed to the achievement of Sustainable Development Goals, including No Poverty, Zero Hunger, Clean Water and Sanitation, and Responsible Consumption and Production. The way for China to cross the turning point of the EKC and increase NUE provides a good experience for agricultural development in many countries in the world, especially in the developing countries.

## 5. Conclusions

In a rapidly developing country such as China, social economic development has dominated the changes in the N budget in farmland. Compared with the high NUE in the developed countries, China's low NUE is mainly attributed to the HCRS and fertilizer subsidy policy. It is unrealistic to reform the existing systems thoroughly, as it involves complex political and economic factors. Nevertheless, with the improvement of agricultural mechanization, China's agricultural management mode is undergoing great changes. In the context of this striking change, the NUE may reach the goal of 0.6 in the 2040s, with a stable crop yield and environmental quality improvements. This shift in farmland N use patterns that China has experienced is being experienced by many other developing countries in the world. Sharing China's knowledge can help those countries still in the first phase of the EKC to cross the turning point.

## Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.geosus.2023.09.003.

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