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Socioeconomic barriers of nitrogen management for agricultural and environmental sustainability

Chenchen Ren [a], Xiuming Zhang [b], Stefan Reis [c,d], Baojing Gu [e,*]

[a] Department of Land Management, Zhejiang University, Hangzhou 310058, People's Republic of China;

[b] School of Agriculture and Food, The University of Melbourne, Victoria 3010, Australia

[c] UK Centre for Ecology & Hydrology, Penicuik, EH26 0QB, United Kingdom

[d] University of Exeter Medical School, Knowledge Spa, Truro, TR1 3HD, United Kingdom

[e] College of Environmental & Resource Sciences, Zhejiang University, Hangzhou 310058, China

***Corresponding Author:**

College of Environmental & Resource Sciences, Zhejiang University, Zijingang Campus, 866 Yuhangtang Road, Hangzhou 310058, PR China.

E-mail: bjgu@zju.edu.cn

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Abstract

Synthetic nitrogen (N) fertilizers support global food production and feed over half of the global population. However, more than half of the N fertilizers applied to croplands are not absorbed by crops, but lost to the environment, leading to low N use efficiency (NUE) globally. Identifying and overcoming socioeconomic barriers to achieve an improvement of NUE and a reduction in N loss is thus key for N management and to attain agricultural and environmental sustainability. In this paper, we compiled the global cropland N budgets at a national scale (1961-2018) and developed robust econometric models to explore the relationship between cropland N use with socioeconomic factors. The results demonstrate that economic development and farm size are the key drivers to improve NUE for agricultural and environmental sustainability. In less developed countries, it is difficult for farmers to access chemical fertilizers, leading to croplands receiving too little N input and at a high NUE, but suffering from soil N depletion. As economic development progresses, more fertilizer is produced and applied, but smallholder farming typically leads to over-fertilization and consequently N losses to the environment. Large-scale farming improves NUE, reduces N loss and benefits agricultural production and environmental protection. Also, interactions between farm size and economic development, international trade, crop and livestock systems, and related policies are important causes for changes in the NUE of the whole agricultural system. Overcoming these socioeconomic barriers especially combining large-scale farming could effectively reduce excessive N inputs and sustain agricultural and environmental N management, while maintaining food production, resulting in a triple-win for food security, poverty alleviation, and environmental protection.

Keywords: Nitrogen Use Efficiency; Environmental Kuznets Curve; Food security; Non-point source pollution; Crop mix

Main finding: Developed economy combined with large-scale farming is vital to achieve better nitrogen management for agricultural and environmental sustainability.

1. Introduction

Agriculture is a dominant source of pollutant emission and its mitigation poses great challenges while safeguarding global food security (Gerten et al., 2020). Global nitrogen (N) fertilizer input to agriculture has exceeded the safe planetary boundary of N, even without accounting for NO_x emissions from fossil fuel combustion (Steffen et al., 2015). Over 100 million tons of N fertilizer is applied to cropland annually to sustain a growing world population (Sutton et al., 2008). However, more than half of this N input from fertilizers is lost to the environment, causing substantial environmental problems such as air and water pollution, as well as biodiversity loss (Zhang et al., 2015). The average N use efficiency (NUE) in the global agricultural system is less than 50%, growing slowly over time, but in some areas such as China and India declining from 1961 (Fowler et al., 2013; Lassaletta et al., 2014). Improving NUE, while maintaining food security, is one key goal for achieving sustainable agricultural production around the world, and plays a vital role in environmental protection (Battye et al., 2017).

The "4R" principle to improve farmland NUE has been proposed, that is, applying fertilizer at the Right rate, Right time, Right place, and from the Right source (Li et al., 2019). Meanwhile, considering soil pH, improving irrigation and preferential use of organic fertilizer are also effective measures to increase NUE at farm scale and are included in Best Management Practices (BMPs) (Castellano et al., 2019; Li et al., 2019; Zhang et al., 2019). Applying BMPs on millions of smallholder farms can lead to a 15-18% reduction in fertilizer use and at the same time to an about 4% increase in NUE according to field trials in China and India with a large number of smallholders (Cui et al., 2018; Jain et al., 2019). However, research indicates the implementation of these measures often encounters socioeconomic barriers. For example, smallholders in China have been proven to prefer over-applying chemical fertilizers with on average a 0.3% increase in chemical fertilizers use for every 1% reduction in farm size (Wu et al., 2018). Meanwhile, farmers' income and the market price of agricultural products can also significantly affect fertilizer application (Zhang and Hu, 2020). Most previous studies focused on technical measures to improve NUE, but to date, a deeper understanding necessary to identify and overcome these socioeconomic barriers to achieve sustainable management of agriculture has not been achieved.

In this study, we reviewed related literature, synthesized historical changes of N management in different countries, calculated N budgets and took NUE as a typical indicator for agricultural and environmental sustainability, and performed statistical analyses to identify potential socioeconomic barriers and discuss approaches to overcome them. The objectives of this paper are as follows: (1) establishing key indicators of temporal and spatial patterns of global NUE; (2) identifying the role of economic development for NUE and environmental sustainability; (3) exploring the relationship between farm size, NUE patterns and environmental protection; (4) modeling their interactive effects with international trade, crop and livestock systems, and policy support.

2. Materials and Methods

2.1 Data collection

Data used in this study are mainly collected from the Food and Agriculture Organization online statistical databases (FAOSTAT) of the United Nations (FAO, 2020). FAOSTAT provides comprehensive and standardized country-level agriculture and economic data all over the world from 1961 to the most recent year available. In this paper, agricultural yield data of each crop in FAOSTAT is mainly used for N harvest calculation in the Coupled Human And Natural Systems (CHANS) model (detailed in Section 2.3). N harvest is the sum of the yield of each crop multiplied by their N content. N fertilizer and manure data from FAOSTAT are used as N input sources to agricultural cropland. The estimate of cropland biological N fixation (CBNF) is based on the area harvested of crops in FAOSTAT and Zhang et al. (2015) of N-fixed rates. Besides, imports and exports of crops and livestock in FAOSTAT are used for the calculation of international trade-related N flows. And gross domestic product per capita (PGDP) in US dollars was also obtained from FAOSTAT representing the economic development of each country. Furthermore, farm size data from the smallholder farmers' database is employed to explore the connections between farm size and N indicators (Lowder et al., 2014).

The China Rural Household Panel Survey (CRHPS) database in 2017 is used to investigate the relationships between farm size and manure input and technology adoption. The CRHPS is a nationally representative survey conducted by Zhejiang University. The original rural household data includes 24,764 households that are registered as agricultural residents. These households consist of 77,132 individuals from 1,439 residential committees and villages, located in 363 selected counties across

China. The survey collected information on household demographic features, agricultural and non-agricultural activities, and household income from these activities. In this paper, we mainly use data concerning agricultural activities including cultivated land area referring to farm size, manure treatment and technology intervention. The interpretation of variables we used are detailed in Section 2.3 and summary statistics are presented in Table S1.

N deposition and irrigation are also important sources of N inputs to the agricultural system. Dataset for global inorganic N deposition rates at a spatial resolution of 2° × 2.5° was derived from (Ackerman et al., 2019). The national-scale cropland N deposition was calculated by aggregating the N deposition map and crop distribution at national boundaries using ArcGIS software. The national irrigation N input to cropland was calculated by multiplying the volume of irrigation with the national average N concentration in irrigation water. National information on global irrigation management is derived from the FAO's Global Information System on Water (AQUASTAT).

2.2 N budget calculation

This study compiled the global cropland N budgets at a national scale for the year 1961-2018 based on the CHANS model. CHANS is a N mass balance model which combines bottom-up N input and output fluxes among 14 subsystems (cropland, livestock, grassland, forest, aquaculture, industry, human, pet, urban green land, wastewater treatment, garbage treatment, atmosphere, surface water, and groundwater) and topdown reactive N fluxes datasets on different (regional, national, global) scale to provide a comprehensive understanding of N cycling and fluxes (Gu et al., 2015). A detailed model introduction can be found in Zhang et al. (2017) and Gu et al. (2015). In this study, the cropland system is identified as the subject in CHANS, the calculation of cropland N budget in each country is formulated in Eq. (1-3):

$$N_{input,i} = N_{fer,i} + N_{man,i} + N_{fix,i} + N_{dep,i} + N_{irr,i} \quad (1)$$

$$N_{output,i} = N_{harvest,i} + N_{gas,i} + N_{runoff,i} + N_{leaching,i} \quad (2)$$

$$NUE_i = \frac{N_{harvest,i}}{N_{input,i}} \quad (3)$$

where $N_{input,i}$ is the total N inputs to the cropland across all crops in the country i, including synthetic fertilizer application ($N_{fer,i}$), manure application ($N_{man,i}$), biological fixation ($N_{fix,i}$), atmospheric deposition ($N_{dep,i}$), and irrigation ($N_{irr,i}$). $N_{output,i}$ is the total N outputs from the cropland, including crop harvest ($N_{harvest,i}$), N gas emissions ($N_{gas,i}$, including NH_3, N_2, N_2O and NO_x emissions), riverine runoff ($N_{runoff,i}$), and leaching to groundwater ($N_{leaching,i}$). NUE (NUE_i) is defined as the ratio of harvest N to total N inputs in cropland system in country i. The estimates of different N outputs from croplands are based on parameters and emission factors nested in the CHANS model.

2.3 Statistical analysis

To estimate the relations between NUE and economic development, we used the Ordinary Least Squares (OLS) regression model to do the longitudinal analysis while controlling for compounding factors such as the crop type and fixed country effect. We estimated the following equation using data from 1961 to 2018:

$$Y_{jt} = \alpha + \beta \cdot PGDP_{jt} + \gamma \cdot PGDP_{jt}^2 + \sum_m \varphi_m q_{mjt} + \varepsilon_{jt} \quad (4)$$

where subscript *j* and *t* denotes country and time, respectively. Y_{jt} refers to NUE. $PGDP$ is the log-transformed value of gross domestic product per capita (US dollars in the corresponding year) representing the economic development of each country. q_m is control variable including crop type and country. β, γ and φ_m are coefficients need to be estimated. Crop type refers to the fraction of the harvested area for fruits and vegetables, which is derived by dividing the harvested area of fruits and vegetables by the total harvested area. We consider crop type as one of main control variables due to its significant effect on NUE (Zhang et al., 2015). We also controlled the fixed effect of each country when we did regression analysis to reduce bias from different countries. α is a constant, ε_{jt} are error items. The regression results are detailed in Table 1 and summary statistics are in Table S1. The reason why we set control variables in equations is to observe the net relationship between independent and dependent variables under the same conditions. For example, crop type is controlled with the purpose that the negative or positive relationship between dependent and independent variables can be deducted from statistical analysis under same crop type.

Additionally, we further estimate the relationship between farm size and manure and technology adoption based on CRHPS data. Manure and technology refer to whether there are any manure application and technical interventions of each household, respectively. Technical interventions are normally provided by governments or corporations e.g. in the form of training classes. It also includes autonomous acquisition through other ways. This variable refers to new technology adoption after active learning or passive intervention. Given manure and technology are binary variables, we used the Logit and Probit models to do analyze the relationship between these variables and farm size. We estimated the following equation based on CRHPS data in 2017.

$$F\{P_i(\ Y_i = 1)\} = \alpha + \beta \cdot Farm\ \ size_i + \sum_m \varphi_m q_{mi} + \varepsilon_i \quad (5)$$

where F refers to the Logit and Probit functions and the subscript *i* denotes household. P_i is the probability of the occurrence of one event ($Y_i = 1$: event occurs; $Y_i = 0$: event does not occur). Y_i refers to whether manure application or technical interventions. $Farm\ \ size_i$ stands for the log-transformed value of cultivated area (ha) of each household, and q_{mi} is the factors affecting including manure treatment, plant type, plot numbers and province. β and φ_m are coefficients that need to be estimated. α is a constant, ε_i are error items. Manure treatment is a category variable representing the way to treat the animal and human excreta, including discharging into the river, biogas digester or municipal sewage pipeline, recycling into cropland and other treatments. Plant type is also a category variable for different cereal crops and other cash crops. Plot numbers are the number of separate farmland plots of the rural household. And we also controlled the fixed effect of each province when we did regression analysis. The regression results are detailed in Table S2 and summary statistics are in Table S1. We did all these statistical regressions in the Stata12.0 software.

3. Results and Discussion

3.1 The spatiotemporal pattern of global NUE

Agricultural N fertilizer input, output and NUE on country-level are subject to substantial spatiotemporal variations (Fig. 1, 2 and Fig. S1). Even though the difference in cereal yield among most regions is insignificant, with the exception of some in Africa, extensive variations in N fertilizer input ranging from less than 40 to over 200 kilograms per ha can be observed (Fig. 1). A wide range of values for NUE are calculated across these regions (Fig. S1). Typically, NUE is considered sustainable in a range between 50% and 90% on the premise that the output of N per hectare exceeds the desired minimum productivity level (Oenema et al., 2015). Productivity refers to N output per area, and the desired minimum productivity level is 80 kg N output per hectare. If NUE remains at a level below 50%, a large amount of N is lost to the environment, leading to environmental degradation. However, soil N mining will occur if NUE is consistently above 90%, which causes damage to soil quality and thus agricultural and environmental sustainability. Most developing countries and emerging economies with lower PGDP show low N output from yield, irrespective of the level of N input. Most countries in Africa have low cereal yield, fertilizer input but higher NUE (Fig. 1 and S1). On the contrary, 220 kg N per hectare (ha) was applied in China in 2017, while only about one-third of this N was harvested in crops, and the rest were lost to the environment (FAO, 2020). In contrast, N outputs per area in most developed regions show higher values than the desired minimum productivity level (Fig. S1). But variations still exist in regions with similar economic development, for instance, the average NUE in the USA is within the sustainable range, while the NUE in the UK is relatively lower with more N loss.

We observe a downward trend of NUE in many global regions such as East Asia and Latin America over time (Fig. 2a), but some regions such as Europe and North America have rebounded to some extent over the past 20 years (Fig. 2b). Currently, the highest NUE is observed in sub-Saharan Africa, followed by Europe and North America. Countries such as China and India where N fertilizer overuse is still prevalent currently have much lower NUE than the world average (Zhang et al., 2015). The Environmental Kuznets Curve (EKC) hypothesis proposes an inverted-U-shaped relationship between environmental pollutants and per capita income, implying that environmental pollutants rise to the peak as income rises, then declines after the peak (Dinda, 2004). N pollution also follows this hypothesis. Accordingly, different countries have been tested their historical N pollutions and identified as being at different stages of an EKC: before the peak, after the peak, or around the turning point (Table S3) (Zhang et al., 2015). We observe an upward historical trend of NUE over time in countries that have progressed beyond the EKC peak, while the opposite trend occurs in countries that have not yet reached their peaks (Fig. 2b, d). This behavior is affected by various socioeconomic factors, not just PGDP. A typical case is Australia, a developed country with high PGDP, but an unexpectedly below-average N input-output ratio across the whole country (Fig. S1). In the following parts of this paper, we will discuss the main socioeconomic barriers and how they affect N sustainable management.

3.2 The role of economic development in the NUE and environmental

sustainability

To test the impact of economic development on N management, PGDP is considered as a typical indicator representing economic performance. A positive U-shaped relationship between PGDP and NUE is found, reflected by the significance of PGDP and its quadratic item to NUE (Table 1). That means NUE first presents a downward trend with economic development, and then turns to increase with PGDP further rising. However, when the quadratic item of PGDP is removed, the main relationship between PGDP and NUE is positive with high significance using all sample countries. It demonstrates that PGDP contributes NUE improvements generally. However, when countries are further grouped according to their position on the EKC, there are diverging results on the relationships within these different groups (Fig. 3). For countries that have passed the EKC peak, economic development has a significant positive effect on NUE. On the contrary, for countries not passing the EKC peak, NUE showed a significant downward trend with PGDP.

The underlying functional relationship between N management and economic development is complex. PGDP growth contributes to increases in fertilizer production and N input. This occurs because industrial facilities and advanced technology are essential for synthetic fertilizer production, which strongly rely on an advanced level of economic development. Thus, the increased accessibility of synthetic fertilizer at the early developing stage with PGDP growth easily leads to over-application, threatening to our environment. Meanwhile, economic development also promotes advances in science and technology and increases the awareness of a need for environmental sustainability, which alleviates N over-use in some countries. As a consequence, increases in economic performance, in turn, promote an increase in NUE. Consequently, economic development contributes to the reduction of pollution inequality across and between different regions, benefiting environmental sustainability (Mi et al., 2020). China has made considerable progress towards sustainable development over the past forty years, mainly due to economic prosperity (Lu et al., 2019). Accordingly, a clearly identifiable turning point occurs with PGDP increases (Fig. 3e), indicating there are vital opportunities of turning to NUE increase for Chinese N sustainable management nowadays (Gu et al., 2018). However, it is worth noting that relying solely on economic growth cannot achieve sustainable N management in agriculture and the environment on its own. Other changes, such as a structural adjustment in the economic system and policy regulations on N management are also important steps to take (Cumming and von Cramon-Taubadel, 2018).

3.3 NUE patterns, environmental protection with farm size

Economic development primarily affects N input. However, we found two different outcomes for N management once countries obtain access to sufficient amounts of chemical fertilizers: in some cases, excessive N inputs are observed, in other cases N is applied at approximately optimum levels. Countries with NUE over 50% and above the N minimum productivity level can be considered as achieving optimum N use levels (Fig. S1). Farm size is one of the main reasons for this difference. In countries after the EKC peak, the average farm size shows no significant correlation with country-level NUE (Fig. 4c), while in countries before the peak, country-level NUE increases with the average farm size (Fig. 4b). Farms are on average larger in countries past the peak, while smaller in countries before the peak (Fig. 4a). Therefore, for countries before the peak, expanding farm size and promoting moderately large scale-farming will have the potential to improve agricultural and environmental performance.

Farm size plays an important role in farmers' input preference and thus affects agricultural N management. We found that there is a significant correlation between farm size and technology adoption (Table S2). That means large-scale farming is more likely equipped with scientific knowledge and advanced technology and equipment. Besides, farm size increases also benefit manure input during farming. That is a great advantage of farming as it can save chemical fertilizers, reduce non-point source pollution and maintain yield (Jin et al., 2020). Then N loss can be lowered with reduced environmental pollution. Meanwhile, large-scale farming can reduce the excessive use of fertilizers and pesticides, then mitigate N effects on the environment and greenhouse gas emissions (Syp et al., 2015; Zhu et al., 2018). Large-scale farming may be less environmentally damaging because it provides a platform for technologies to be adopted and applied (Unay and Bojnec, 2015). Specially, farmers with large-scale farmland prefer fixed inputs due to cost-effectiveness considerations, and have better management knowledge and advanced technology, etc., rather than over-use of fertilizers and pesticides (Ren et al., 2019). Thus, it is likely that they adopt new technologies and apply science-based management knowledge such as using manure as chemical fertilizer replacement (Fig. S2), promoting sustainable N use and environmental protection. Meanwhile, agricultural yield doesn’t compromise significantly with farm size increase (Wu et al., 2018), leading to high NUE observed on large-scale farms. Comparatively, smallholders affected management practices by using more chemical fertilizers (Li et al., 2021). Agricultural management knowledge and environmental awareness vary substantially among smallholder farms, which may inhibit agricultural production and environmental protection (Oliver et al., 2020).

Per ha inputs of machinery, energy and fertilizers to global crop production have increased by 137% during the period from 1961 to 2014, benefiting agricultural production efficiency (Pellegrini and Fernandez, 2018). It means that if new technologies are adopted by both large and small farmers, agricultural outputs, as well as environmental benefits, will increase (Zhang et al., 2016). However, the technology adoption rate is significantly constrained by small farm size and a large number of smallholders (Lybbert and Sumner, 2010; Long et al., 2016).Taking China as an example, where smallholder farms dominated, water-saving technologies such as drip and sprinkler irrigation have been available for many years, but are still not widely applied (Fig. S3). Therefore, it is insufficient to only emphasize the implementation of BMPs, while not considering the role of farm size (Wang et al., 2017). Although government agencies have promoted land consolidation to increase farm size for decades, so far only a little progress has been made because of substantial transaction costs and policies distortion in China (Tan et al., 2006; Wu et al., 2018). Achieving sustainable N management in agriculture and environment is quite difficult in cases where small-scale farming is the dominant form of organization, despite policies designed to reform the agricultural sector, such as increasing market access through online platforms or subsidizing small farmers to improve their welfare (Levi et al., 2020). Thus, promoting an effective increase in farm size, thereby increasing agricultural productivity and achieving more sustainable N management is of great significance. It is worth noting that there are also some negative effects of large-scale farming including biodiversity loss, soil erosion and nutrient loss, typically in hilly areas (Marcacci et al., 2020; Li et al., 2020a; Li et al., 2020b). The risk of large-scale farms facing would increase when tackling market fluctuations, which may exert negative pressure on the economy (Ritchie and Ristau, 1986; Levins and Cochrane, 1996). Given business considerations, farmers may raise the rate of N fertilizer application when dealing with climate change (Houser and Stuart, 2019). Accordingly, farm size should be improved appropriately based on local natural and socioeconomic conditions. These negative effects need to be taken into consideration when implementing large-scale farming to maximize its advantage for agricultural and environmental sustainability.

3.4 Interactions between economic development, farm size and other socioeconomic barriers for agricultural and environmental sustainability

Countries with high level of economic development usually tend to develop large scale-farming (Adamopoulos, 2010; Lesiv et al., 2018). More precisely, the average farm size generally increases in line with PGDP. NUE accordingly substantially improves in a well-developed economy with large-scale farming such for instance observed in the USA. However, this does not apply to all countries. China's rapidly developing economy in recent years has not resulted in major improvements in its average farm size (Wu et al., 2018). As a result, NUE in China has remained at a low level for a long time. It can be seen that the interactions between economic development and farm size may have different effects on NUE at the regional scale.

Besides, farm size affects NUE not only through technology adoption, but as well through an increase in manure recycling based on the coupling of crop planting and livestock (Jin et al., 2020). Unrecycled manure in livestock systems is normally processed by open-air composting and then produces a large amount of NH_3 volatilization and N losses, leading to air pollution and affecting water quality through atmospheric deposition (Ju et al., 2017). If livestock manure is recycled to cropland, it contributes to increasing NUE and reducing N losses to ecosystems (Xia et al., 2017). The major challenge for achieving this lies in coordinating the spatial relationship between livestock and crop systems at a regional scale (Zhang et al., 2019). This needs to be based on large-scale operations, otherwise substantial socioeconomic and transportation costs will be incurred by a large number of smallholder farms (van Grinsven et al., 2018). Besides, small-scale crop-livestock systems would be with more greenhouse gas emissions (Ortiz-Gonzalo et al., 2017). Consequently, small-scale farming hinders the recycling of manure and the improvement of NUE, then damaging the environment (Jin et al., 2020).

Considering economic development and international trade, we found developed countries generally have high agricultural N productivity (Fig. 1 and S1), not only meeting domestic demand, but also exporting through international trade, for example the USA and European countries (Fig. S4). Generally, these countries are not agriculture-based economies, attaching much importance to food security with more cereal domestic production but fewer imports (Fig. S4f). For developing countries in Asia, except China, the situation is different. Large production of vegetables and fruit for export makes up a significant part of their national economy. In contrast, cereal production output in China has rapidly increased in recent years, while imports have increased at the same time, accompanied by a large production volume of vegetables, fruit and livestock. A varied dependence on international trade mainly occurs due to different economic development levels, affecting the domestic crop mix (Sun et al., 2018). Although crop cultivation and livestock breeding are strongly based on local environmental conditions, the interaction between economic development and international trade also affects crop mix, hence leading to NUE differences across the world (Zhang et al., 2015).

Policy support also plays a critical role for N sustainable management. Relying on farm-level BMPs only has not made a major difference and such approaches alone are unlikely to achieve sustainable N management (Kanter and Searchinger, 2018). In countries with N use close to optimum levels, governments are continuously seeking a balance with farmers to promote sustainable development (Fig. 5). Farmers naturally pursue strategies aiming at maximizing individual profits, while governments aim to balance environmental, resource efficiency and sustainability objectives. Effective governance and policies are key to achieving N sustainable management (Andrijevic et al., 2020). Thus, promoting BMPs needs to be underpinned by policy interventions, regulation, and investment (Kanter and Searchinger, 2018; Pretty et al., 2018). Besides, considering all stakeholders in the agricultural food production and consumption chain, including fertilizer manufacturers, farmers, agricultural consultants, processors, traders, retailers, consumers is vital for governments to make progress towards sustainable development (Kanter et al., 2020). Such integrated approaches will specifically benefit countries that have not reached optimal N use level and help to overcome socioeconomic barriers and achieve N sustainable management.

4. Conclusion

This paper provides a comprehensive and integrated assessment of the socioeconomic barriers which need to be overcome to achieve sustainable N management in agriculture and the environment. Our analysis highlights that economic development and farm size have a substantial influence on agricultural and environmental sustainability. Meanwhile, it also underlines their interactions with international trade on crop mix, crop and livestock systems on manure recycle, and related policies in the sustainable development of agriculture. A better understanding of the role of socio-economic barriers to agricultural and environmental N management can provide opportunities to achieve sustainability, especially for developing countries where soil

N mining or over-use of chemical fertilizers is prevalent. Robust evidence discussed in this study suggests that overcoming socioeconomic barriers is critical to promote the development of sustainable agriculture and the environment. Future research needs to focus on a detailed quantification of the costs and benefits to identify feasible pathways to overcome these barriers and achieve progress towards the sustainable development goals.

Declaration of competing interest

All authors have no conflicts of interest to report.

CRediT authorship contribution statement

Chenchen Ren: Methodology, Software, Formal Analysis, Writing – Original draft, Visualization. **Xiuming Zhang:** Validation, Investigation, Data Curation, Writing – Review and editing. **Stefan Reis:** Validation, Writing – Review and editing. **Baojing Gu:** Conceptualization, Writing – Review and editing, Visualization, Funding acquisition.

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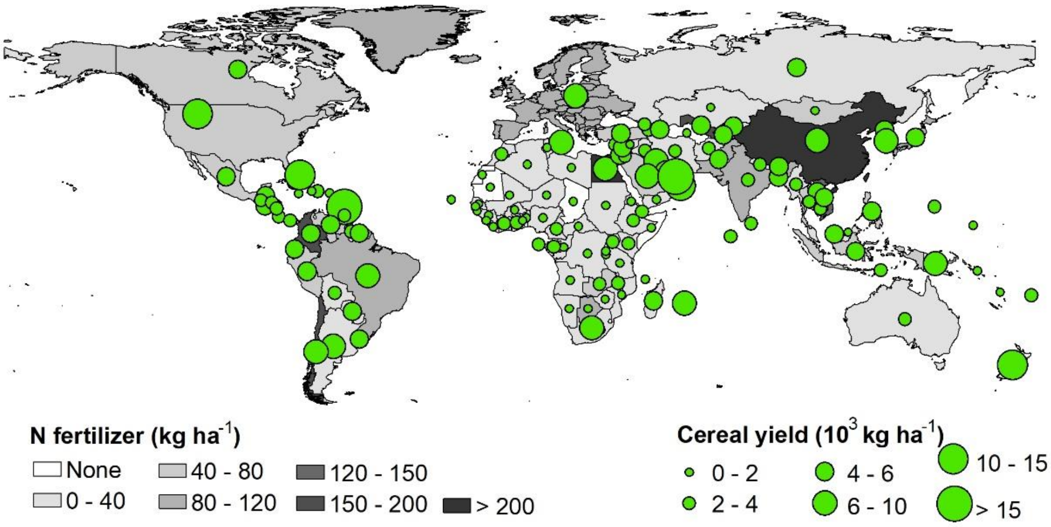

Fig. 1 Spatial variations in nitrogen (N) fertilizer input and cereal yield across different countries in 2017. N fertilizer (grey scale) depicts total N use (kilograms) from all chemical fertilizer products divided by the harvested area (hectare). Rice milled equivalence is used for cereal yield representing agricultural productivity levels.

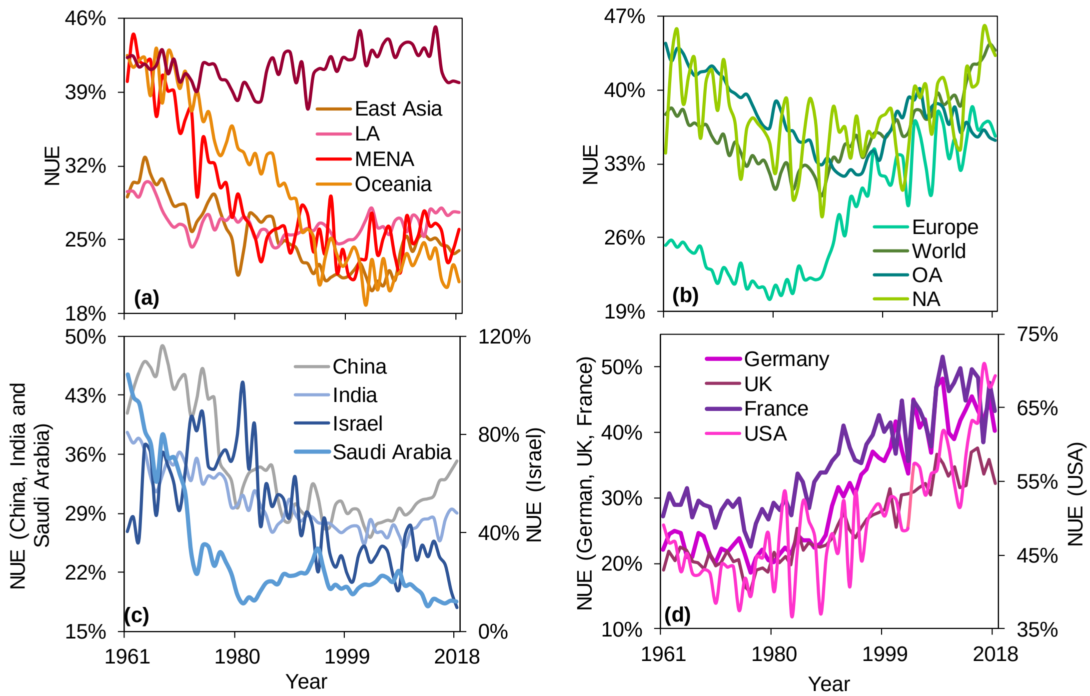

Fig. 2 N use efficiency (NUE) historical changes across different regions. LA, Latin America; MENA, Middle East and North Africa; SSA, Sub-Saharan Africa; OA, Other Asian countries; NA, North America; UK, United Kingdom; USA, United States of America. Panels (a) and (b) show NUE in different regions across the world; (c) and (d) show NUE in countries before and past the Environmental Kuznets Curve (EKC) peak, respectively. In panel (c), values for Israel are shown on the secondary axis, all other countries refer to the primary axis. Similarly, values for the USA in panel (d) are shown on the secondary axis, all other countries refer to the primary axis.

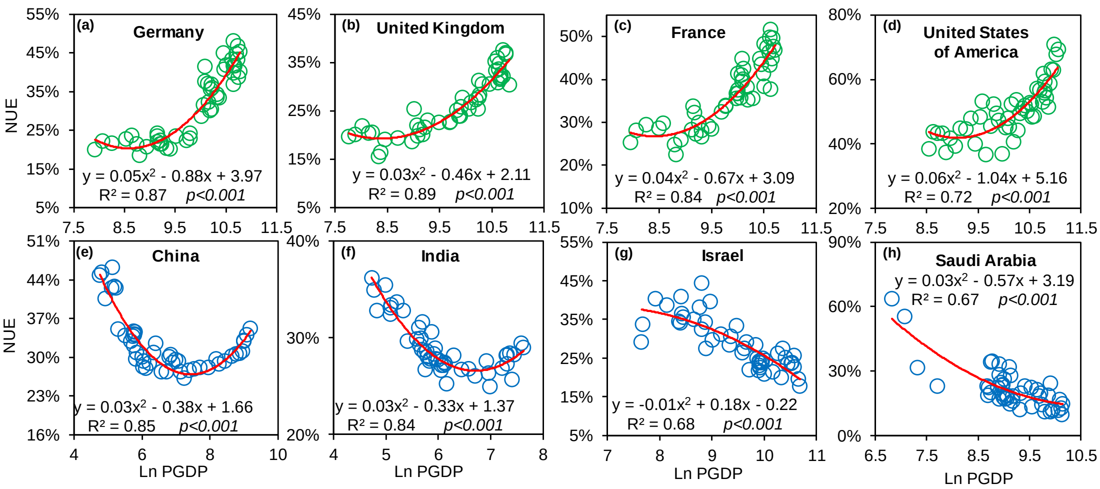

Fig. 3 NUE changes with economic development across different countries. Green circles depict countries after the EKC peak; blue circles countries before the EKC peak. PGDP represents the gross domestic product per capita (US dollars in the corresponding year) in each country. The detailed regression analysis of N input and NUE with PGDP is described in Table 1.

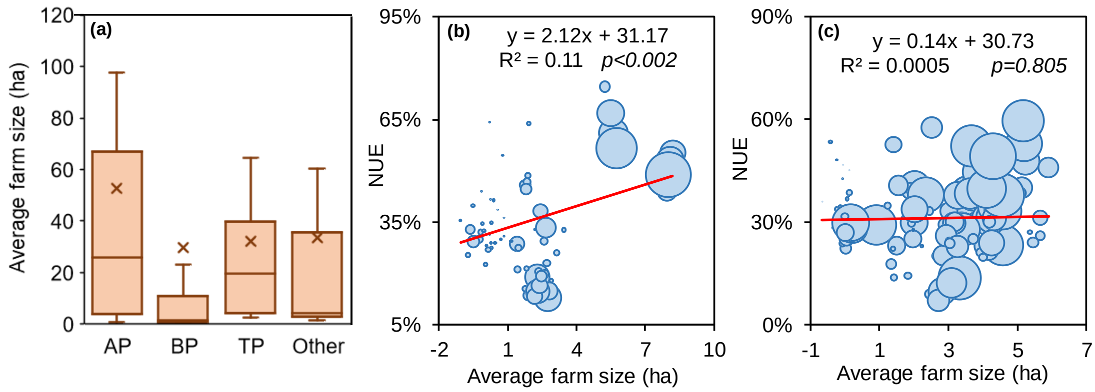

Fig. 4 Farm size and NUE in different countries. (a) AP, BP and TP are countries after (AP), before the EKC peak (BP) and around the turning point of EKC (TP), respectively. Other refers to countries except those explicitly labeled, namely with an insignificant relationship of EKC. Normally, the EKC cannot be well evaluated in these countries yet owing to the limited change in the country's PGDP (Zhang et al., 2015). Farm size data in this panel is from year 2010. The vertical line in the middle is the mean error bars showing 97% percentiles. And the extremes over this error line have been removed. The upper, lower and middle lines of the rectangle are shown values on 75%, 25% and 50% percentiles, respectively. The "×" represents the average. (b) and (c) is the relationship between NUE and farm size in countries before the EKC peak and after the EKC peak, respectively. The effect of crop type has been controlled in panel (b) to show the net effects between farm size and NUE. Average farm size has been log-transformed on the X-axis of the two panels. Details of regression analysis are in Table S4. The bubble size of each data point in (b) and (c) is proportional to the gross domestic product per capita (US dollars in the year) in each country with 56, 965 dollars of USA as a reference. We use data from 1960 to 2010 in panels (b) and (c).

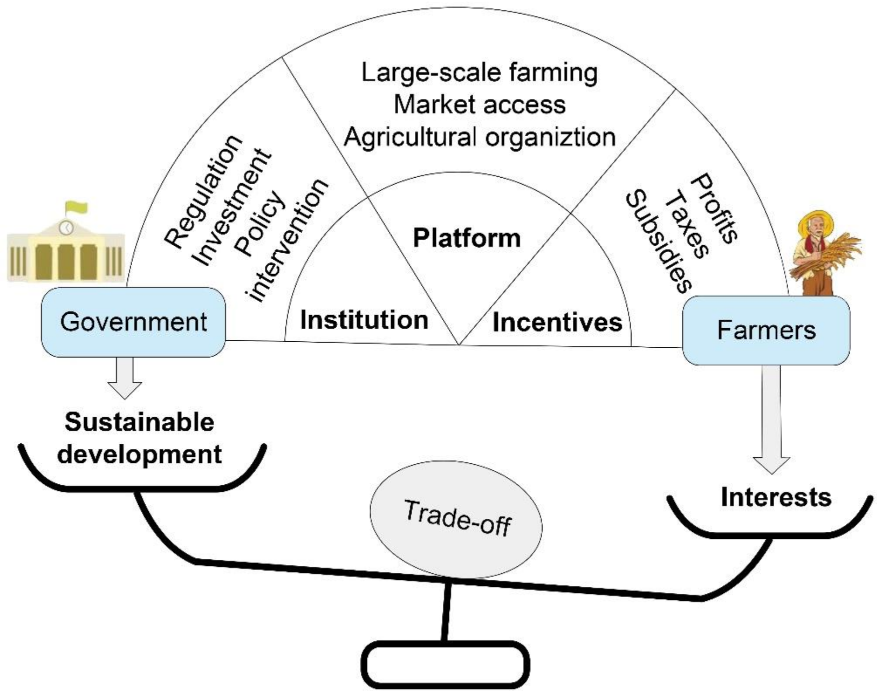

Fig. 5 The trade-off between government and farmers for sustainable N use in agriculture. Farmers and governments have different goals in social development, namely sustainable development and individual interests respectively, leading to both in a continuous trade-off. Regulation, investment or policy intervention are normally proposed by governments. Meanwhile, the corresponding incentives such as taxes or subsidies are received by farmers. Nowadays, farmers' interests weigh much more in most regions around the world. Thus, fully using platforms such as large-scale farming during trade-off will be a critical path for agricultural N sustainability.

Table 1 Regression analysis results of NUE with economic development

	Without the quadratic term of PGDP			With the quadratic term of PGDP		
	NUE in AP group	NUE in Other group	NUE using all sample	NUE in AP group	NUE in Other group	NUE using all sample
Ln PGDP	0.05^{***}	-0.01^{***}	0.05^{***}	-0.09^{***}	0.04^{***}	-0.02^{**}
Ln $PGDP^2$				0.01^{***}	-0.03^{***}	0.002^{***}
Crop type	-0.53^{***}	-0.21^{***}	-0.24^{***}	-0.43^{***}	-0.20^{***}	-0.25^{***}
Country	Yes	Yes	Yes	Yes	Yes	Yes
N	1323	6103	7426	1323	6103	7426
Adjust R^2	0.75	0.79	0.78	0.77	0.79	0.78

$^{*}p < 0.05$, $^{**}p < 0.01$, *and* $^{***}p < 0.001$. The country group refers to the different group data used in regression analyses. AP refers to countries after the EKC peak. “Other” means other countries except for countries after the EKC peak. Ln PGDP is the log-transformed value of gross domestic product per capita (US dollars in the corresponding year) representing the economic development of each country. Crop type refers to the fraction of the harvested area for fruits and vegetables. “Yes” for variable of country indicates controlling for the fixed effect of each country when conducting the regression analysis. The results indicate that in countries which have progressed beyond the EKC peak economic development substantially promotes NUE, while in other countries NUE decreases with economic development.