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SPECIAL FEATURE: ORIGINAL ARTICLE

Globally-Consistent National Pathways towards Sustainable Food and Land-use Systems

Reforming China's fertilizer policies: implications for nitrogen pollution reduction and food security

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Abstract

Reactive nitrogen (N) is a requisite nutrient for agricultural production, but results in greenhouse gas and air and water pollution. The environmental and economic impacts of N fertilizer use in China are particularly relevant, as China consumes the largest amount of N fertilizer in the world to meet its soaring food demand. Here, we use an agro-economic land system model (MAgPIE) in combination with a difference-in-differences econometric model to provide a forward-looking assessment of China's fertilizer policies in terms of removing fertilizer manufacturing subsidies and implementing measures to improve agricultural nutrient management efficiency. Our model results indicate that enhancing soil N uptake efficiency and manure recycled to soil alongside fertilizer subsidy removal can largely reduce N fertilizer use and N losses and abate N pollution in the short and long term, while food security remains largely unaffected. Enhancing soil N uptake efficiency appears to be decisive to achieving China's national strategic target of zero growth in N fertilizer use. This study also finds that improving agricultural nutrient management efficiency contributes to higher land productivity and less cropland expansion, with substantial benefits for the environment and food security.

Keywords Fertilizer manufacturing subsidy · Soil nitrogen uptake efficiency · Manure recycling · Nitrogen surplus · Food prices

Introduction

Reactive nitrogen (N) fertilizer is essential for agricultural production (Bodirsky et al. 2014), especially in China, which faces increasing food demand driven by population growth and changing dietary patterns (Zhang et al. 2013; Gu et al. 2017; Bodirsky et al. 2020). China is the largest N fertilizer producer in the world, and N fertilizer has contributed substantially to increased food production (Gu et al. 2015; Cui et al. 2018; Wu et al. 2018). However, the average N fertilizer intensity in China is more than three times higher than the global average, amounting to 218.3 kg/ha in 2010 (FAO 2010). In contrast, N use efficiency (NUE), defined as the ratio of N in harvested crops to the sum of N derived from synthetic fertilizer, manure, biological fixation, and deposition, was only 0.25 in 2010, half of the global average and one third of that in North America (Zhang et al. 2015). Overuse of N fertilizer imposes a great challenge to the nitrogen planetary boundary (Steffen et al. 2015; Campbell

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et al. 2017; Chang et al. 2021) and results in severe environmental problems, including soil acidification, water pollution (NO_3–N, NH_4–N), air pollution (NH_3, NO_X), and greenhouse gas (GHG) emissions (N_2O) (Galloway et al. 2008; Guo et al. 2010; Chen et al. 2018; Yu et al. 2019; Jin et al. 2021b).

Concerned with food availability, a fertilizer manufacturing subsidy (FMS) policy was in effect to provide the cheap use of electricity, natural gas, and transportation, as well as an exemption from value-added taxes in the 1990s (Li et al. 2013; Ju et al. 2016). With a rising concern about the negative environmental impacts of N fertilizer overuse (Wu et al. 2018; Yu et al. 2019; Zhang et al. 2020), the Chinese government has been endeavoring to curb its N fertilizer use. The FMS has been almost entirely removed by 2015 to disincentivize the excessive use of N fertilizer (Li et al. 2014). Furthermore, the Ministry of Agriculture and Rural Affairs in 2015 also initiated the strategy of "Zero Growth in Synthetic Fertilizer Use" (hereafter called "Zero Growth Strategy") aiming to enhance NUE and thus further reduce N fertilizer use. Therefore, four specific measures were implemented: (a) formulating fertilization standards for different regions and crops to promote precise fertilization; (b) adjusting the structure of N, P, and K fertilizers and applying high-efficiency fertilizer; (c) adopting new fertilization methods by promoting a soil quality measurement program and mechanized fertilization; (d) substituting organic manure for synthetic fertilizer (Lin et al. 2022b). As these measures require more labor or machinery inputs, the government subsidizes the farmers for the extra costs.

Improving NUE has been effective in reducing the adverse environmental impacts of N fertilizer while increasing yields (Zhang et al. 2015; Gu et al. 2017). Specific measures such as technical training, and field nutrient measurement and nutrient balances, as well as better dosing, multiple application or slow-release fertilizers (Huang et al. 2008; Cui et al. 2018) are suggested to improve nutrient management efficiency (NME). Targeting agricultural input subsidies toward more efficient use of N fertilizer and manure is likely to reduce N losses (Cui et al. 2018). These measures are often assessed separately, although existing studies suggest that there are small trade-offs with respect to environmental improvements and food security associated with nutrient efficiency improvement (Lassaletta et al. 2014; Bodirsky and Müller 2014; Brunelle et al. 2015). However, as environmental and economic outcomes depend on the underlying socioeconomic trends (Lotze-Campen et al. 2018), simply assuming that China's current socioeconomic development trajectory will remain constant is unlikely to draw realistic policy implications. Thus, the trade-offs and synergies of China's fertilizer policy reform warrant exploration by taking socioeconomic dynamics into account.

Empirical methods (e.g., field experiments and econometric approaches) and modeling approaches are often used to assess the impacts of agricultural management practices on fertilizer use and nutrient efficiency. Studies based on field experiments and econometric methods are informative regarding the effectiveness of specific management practices (e.g., no tillage, and nitrification inhibitors) (Chen et al. 2014; Feng et al. 2016; Xia et al. 2017; Li et al. 2018) or existing policies such as the European Common Agricultural Policy (Arata and Sckokai 2016; Czyżewski 2020). Empirical and experimental studies not only provide evidence on the current situation, but also derive parameters for modeling-based studies, although it is often difficult to make a forward-looking assessment. In contrast, integrated assessment models take both biophysical and socioeconomic dynamics and their interaction into account, while depending on stylized assumptions about effectiveness of measures and policies (Gaupp et al. 2021). It is essential to accommodate efforts from these two types of studies to improve understanding about long-term effects.

Few studies combine modeling approaches with evaluations of actual policies; van Wesenbeeck et al.'s (2021) study is an exception in that it uses a general equilibrium model and investigates the impacts of policies related to synthetic fertilizer use on agricultural production, environmental pollution, and rural income. In addition, existing literature mainly focuses on the impacts of fertilizer subsidies for farmers on agricultural production (Rosegrant and Herdt 1981; Ricker-Gilbert et al. 2011; Li et al. 2014), while ignoring fertilizer manufacturing subsidies, which are prevalent in developing regions such as India and sub-Saharan Africa (Takeshima 2015; Praveen et al. 2017) and an important part of China's fertilizer policy reform. Hence, this study aims to fill this research gap by revealing environmental and economic implications of China's fertilizer policy reform and shed light on the fertilizer policy reform in a broader context.

To this end, we use an agro-economic land system model–MAgPIE (Model of Agricultural Production and its impact on the Environment) coupled with an econometric method to quantify the impacts of reforming China's fertilizer policies with regard to environmental and economic outcomes in a forward-looking manner by considering both biophysical and socioeconomic dynamics. Our study proceeds in two distinct steps. We first estimate the changes in N fertilizer price and the efficiency of agricultural nutrient management induced by the fertilizer policy reform. We then incorporate these policy effects into the modeling framework to further assess the environmental impacts in terms of N fertilizer use, N surplus and N pollution, while quantifying the economic impacts related to food price, food self-sufficiency, and crop productivity. A sensitivity analysis with regard to key parameters is also conducted. China is an important part of the FABLE (The Food, Agriculture, Biodiversity, Land-Use, and Energy) consortium exploring transformation pathways toward sustainable food and land-use systems by 2050. Evaluating the impacts of China's fertilizer policy reform using MAgPIE in this study contributes to the understanding of potential sustainable agricultural development pathways, as an extension of the previous FABLE reports (FABLE et al. 2020).

Materials and methods

Agro-economic land system model

MAgPIE is an agro-economic land system model with a cost minimization objective function of fulfilling the demand for agricultural products (Popp et al. 2017; Lotze-Campen et al. 2018; Dietrich et al. 2019; Wang et al. 2020). This study uses MAgPIE version 4.3.4 with 12 world regions and 400 clusters (Supplementary Information-SI, Fig. SI-1) grouped together according to their geo-economic conditions (Dietrich et al. 2019), of which 289 clusters are allocated to China. The model runs in a dynamic recursive mode from 1995 to 2060 with a five-year interval. For agricultural production components, the model covers 24 main production activities including 19 crop commodities and five livestock commodities (Table SI-1). Agricultural demand is classified into four subcategories of demand: food, material, feed, and biomass (Dietrich et al. 2019). Food demand is mainly driven by population and income growth (Bodirsky et al. 2020), while material demand is assumed to be proportional to food demand. Demand for animal feed is derived from the feed basket content, while biomass demand is calculated according to biofuel production. Agricultural production is endogenously determined in the optimization, based on its costs. The major costs comprise the costs of production input factors (including labor, capital, energy, and related costs), land conversion costs, domestic transport costs, fertilizer costs, irrigation costs, trade costs, and technological investments (Lotze-Campen et al. 2008; Popp et al. 2014; Dietrich et al. 2019). Biophysical constraints such as land and water availability, crop yields, and terrestrial carbon are prescribed at the 0.5-degree grid level, which is derived from the global crop, hydrology, and vegetation model LPJmL (Lund-Potsdam-Jena model with managed Land) (Schaphoff et al. 2018).

In addition to the average yields, MAgPIE calculates land-use intensity as another measure of land productivity. The index of land-use intensity in MAgPIE is computed based on endogenous technical changes, following the induced innovation theory (Ruttan 2002), which distinguishes MAgPIE from other models such as GLOBIOM and IMPACT (Valin et al. 2013; Robinson et al. 2014). Land-use intensity represents the increase of yields due to technical changes such as R&D, infrastructure, and management (Dietrich 2012; Dietrich et al. 2014; Wang et al. 2020). Investments in technological change trigger land-use intensification, which in turn triggers yields increases. The intensification triggered by an investment depends on the investment-yield ratio, which in turn depends on the current agricultural land-use intensity. The higher the current land-use intensity level is, the more expensive will be the additional intensification. A more detailed description of the association between land-use intensity and average yields can be found in Wang et al. (2020). Labor costs are implicitly considered in the model as part of production factor requirement costs (Dietrich et al. 2014, 2019). Crop yields can be increased via expansion of irrigated areas, requiring blue water that is available in limited quantities for each cluster (Bonsch et al. 2015). Food prices are shadow prices of domestic demand and trade constraints, which are determined by the solution of the total production cost minimization, indicating the scarcity of the resources used for food production (Wang et al. 2016). In addition to production costs, MAgPIE also accounts for domestic transport costs to the nearest market and trade costs including trade margins and tariffs. Detailed information on the model can be found in Dietrich et al. (2019). The framework of this study is also illustrated in Fig. SI-2.

For this study, we focus on the model results in 2030 and 2060, as China pledges to peak GHG emissions by 2030 and reach climate neutrality by 2060 for climate protection given that agriculture is a major source of non-CO_2 emissions. MAgPIE estimates N pollution from land-use changes and agricultural activities, and calculates N surplus that is released to the environment. N surplus is defined as the difference between N inputs in agriculture (including both synthetic and organic N fertilizer) and N in agricultural products. Since the model has a detailed representation of the nitrogen cycle, it estimates N pollution, including ammonia (NH_3), nitrate (NO_3^-), N_2O and NO_2, which are related to the animal waste management system and cultivated soils (e.g., organic and synthetic fertilizers) (Bodirsky et al. 2012). Fertilizer application is associated with crop production via crop-specific N requirements. Synthetic fertilizer and manure are two major sources of N inputs in agricultural production. The fertilizer application is calculated by the fertilizer requirements to obtain a certain production under a given fertilization technology level (Bodirsky et al. 2014). Manure is estimated by subtracting the nutrients contained in the biomass of slaughtered animals from the feed intake based on a given animal waste management system, which is reflected in the indicator of manure recycled to soil (MRS). According to what animals eat and where their manure remains, the model distinguishes four categories of general animal waste management systems: (a) confined animals that receive concentrated feed and crop residues; (b) grazing animals on pastures where the manure stays on pastures; (c) grazing animals on pastures where the manure is collected as household fuel; and (d) grazing animals eating crop residues on stubble fields. It is worth mentioning that there are two main interaction mechanisms among crop residues, feed, and manure according to the usage. Crop residues can be used for feed, part of which will be converted to manure by feeding to livestock, and crop residues are used as building material or burned on the field. Using a balanced approach, the remaining residues are recycled to soil and are counted in the nitrogen budget as N input replacing synthetic fertilizer.

To improve the representation of China, we modify the core MAgPIE based on the latest data and policies related to Chinese agriculture (MAgPIE-China). In this version, we mainly calibrate the key indicator–fertilizer use in China for the historical period by incorporating the effects of China's fertilizer policy reform on NUE and N fertilizer price.

Estimation of changes in N fertilizer price and soil N uptake efficiency

Removing FMS to correct N fertilizer price and improving NUE are the main pillars of China's fertilizer policy reform (van Wesenbeeck et al. 2021) and are important for reducing N fertilizer use (Li et al. 2013; Zhang et al. 2015). It is important to obtain the accurate magnitudes and trends of N fertilizer price and NUE that were caused by this policy reform for assessing the long-term policy impacts in a forward-looking manner in MAgPIE-China. Thus, we estimate the policy effects on N fertilizer price and NUE using econometric methods with observed data to enhance the representation of the two key mechanisms.

We use two sets of observed data, namely, the fertilizer price index and the amount of N fertilizer use to estimate the effect of removing FMS on N fertilizer price. First, we calculate the effect of FMS removal on fertilizer price by dividing the total FMS [18 billion USD in 2010 (Li et al. 2013)] by the amount of synthetic fertilizer use. Alternatively, we derive the incremental N fertilizer price due to the FMS removal policy as the difference between the relative change in fertilizer price in the USA (− 16%) and China (4%) after 2015. We assume a counterfactual situation, in which the FMS would still exist in China after 2015 and the fertilizer price index trend would be similar to that in other countries without this policy. Due to data availability, we derive the counterfactual price dynamics for China by applying the N fertilizer price dynamics in the USA onto the Chinese price in 2015. The fertilizer price index in China and the USA displayed similar trends from 2003 to 2015 and diverged in 2016 (Fig. SI-3), which supports our assumption.

NUE is represented by a regional-specific and broader measure in the model, that is, soil N uptake efficiency (SNUpE), to reflect the fertilization technology level of farmers additional to the climatic and biophysical conditions. SNUpE is exogenously determined in the model and is equal to the ratio of N^{output} in crop production (nitrogen content in harvested biomass and crop residues minus biological fixation and seeds) and N^{input} to cropland (including eight sources such as synthetic fertilizer and manure). N^{output} includes N embodied in crop harvest, which is endogenously determined during the optimization. Higher levels of SNUpE imply fewer amounts of N fertilizer required for crop production. Detailed information about SNUpE estimation can be found in SI.

With regard to the parameter of SNUpE, we first employ a staggered difference-in-differences (DID) method to estimate the effects of the FMS removal policy and nutrient management efficiency (NME, refers to measures for improving SNUpE and MRS) on N inputs and N outputs derived from N fertilizer ($N^{\mathrm{fertilizer}}$) and harvested crops (N^{harvest}), as these policies were implemented at a different time across counties in China. We then incorporate the changes of N fertilizer ($N^{\mathrm{fertilizer}}$) and harvested crops (N^{harvest}) into an N balance equation to calculate the change of SNUpE (SI–SNUpE calculation). Country-representative household-level data from a survey in the key rice production areas in China conducted by the Ministry of Agriculture and Rural Affairs during 2014–2018 are used for the econometric estimation. By incorporating the policy effects on $N^{\mathrm{fertilizer}}$ and N^{harvest} in terms of fertilizer reduction (− 0.155, Table SI-2) and yields increase (0.080, Table SI-3) in 2015 and 2020, we update the SNUpE in the corresponding years using the N balance equation (Fig. SI-4). Since rice is a major staple food in China and the fertilizer policies mainly focus on staple foods, we assume the same SNUpE effect when the fertilizer policy reform applies to other crops.

Scenarios

We parameterize the scenarios according to the middle-of-the-road socioeconomic pathway (SSP2), which implies a continuation of current development patterns (O'Neill et al. 2017). In SSP2, population dynamics and global demand for crop and livestock products are assumed to increase moderately. Production and international trade remain fairly regionalized. The growth rates of crop yields decline slowly over time, but low-income countries catch up to a certain extent (Popp et al. 2017).

To assess the effect of China's fertilizer policy reform, two key policy elements are considered in policy-as-usual (PAU). The SubsidyRemoval and NMEModerate scenarios represent the two key policy elements of China's fertilizer policy reform on N fertilizer price and SNUpE, which are estimated based on the above calculation and econometric estimation, respectively:

Table 1 Scenario specifications in terms of nutrient management efficiency (NME), fertilizer prices, and emission costs

		Year	CAU	PAU			AMB		
				Overall effect	Sub-scenarios		Overall effect	Sub-scenarios	
					SubsidyRemoval	NMEModerate		NitrogenTax	NMEHigh
NME	SNUpE	2015	0.46	0.52	0.46	0.52	0.52	0.46	0.52
		2030	0.46	0.58	0.46	0.58	0.61	0.46	0.61
		2060	0.46	0.58	0.46	0.58	0.69	0.46	0.69
	MRS	All	Low	Low	Low	Low	High	Low	High
Fertilizer price (USD/ton N)		Since 2015	600	930	930	600	600	600	600
Emission cost (USD/ton N)		Since 2015	NO	NO	NO	NO	YES	YES	NO

- The N fertilizer price in the SubsidyRemoval scenario increases to 930 USD/ton N after 2015.
- The SNUpE in the NMEModerate scenario improves to 0.52 in 2015 and 0.58 in 2020, and after that it remains constant.

To further explore alternative options for policy implementation, the AMB scenario represents high ambitions toward an environmentally sustainable land-use transformation pathway, consisting of NitrogenTax and NMEHigh sub-scenarios, which implies that high ambitions in combating N pollution and emissions occur hand-in-hand with the implementation of NitrogenTax and NMEHigh scenarios. The AMB scenario is assumed to capture the potential effect of more ambitious measures of nitrogen tax and high-level NME:

- A prescribed NitrogenTax is assumed, in which N_2O emission is taxed according to the 100-year global warming potential suggested by the IPCC AR5 (Soergel et al. 2021).
- In the NMEHigh scenario, in addition to a higher improvement in SNUpE following Bodirsky et al. (2014) and Zhang et al. (2015), a higher enhancement in MRS is set, which increases the role of organic fertilizer represented by animal manure (Fig. SI-4).

With the estimate of policy effect from the DID regression model, we are able to construct a counterfactual-as-usual (CAU) scenario, which represents the counterfactual situation where there would be no fertilizer policy reform in China. The CAU scenario assumes a constant SNUpE of 0.46 after 2010 with a low share of MRS and N fertilizer price (600 USD/ton N at a constant price in 2005) in China (Table 1).

Additionally, a complementary analysis of GHG tax scenarios of different tax levels and types (NitrogenTax, NitrogenTax330, CarbonTax, and PhaseinNTax&SM) is conducted to compare the effectiveness of emissions mitigation and economic responses between FMS removal and GHG taxes (Table SI-4). To test the robustness of the subsidy removal policy (Brunelle et al. 2015), we further simulate additional scenarios with fertilizer prices ranging from 720 to 1050 USD/ton N with an incremental interval of 30 USD/ton N. Furthermore, we also conduct a sensitivity analysis for the four sub-scenarios and their components, that is, SNUpE, MRS, and their combinations (PhaseinCTax&SM and PhaseinNTax&SM), to identify the feasibility of meeting the target set in the "Zero Growth Strategy" in the long term (Table SI-5).

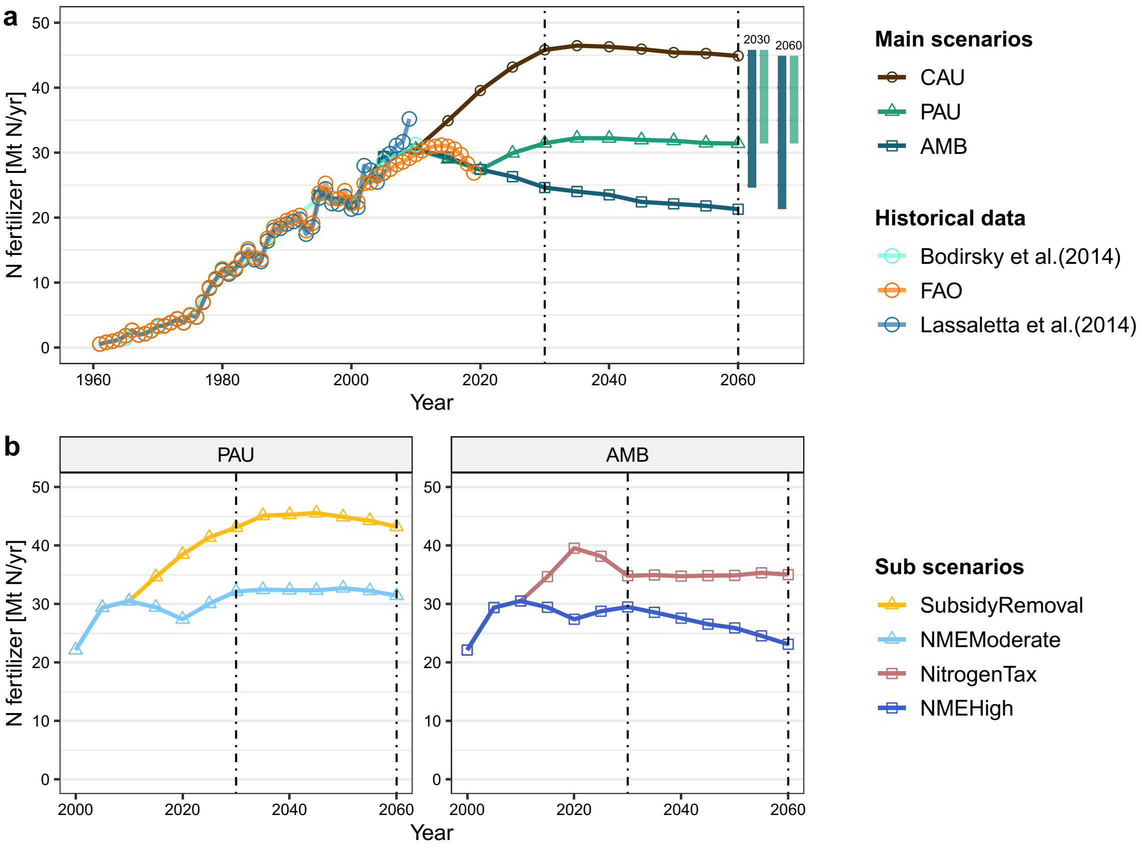

Fig. 1 N fertilizer use in China in the main scenarios (**a**) and their sub-scenarios (**b**). The validation data of N fertilizer amount used in the historical period are based on Bodirsky et al. (2014), Lassaletta et al. (2014), and FAOSTAT. **a** N fertilizer amount used in 2020 in the PAU scenario is slightly higher than that in the AMB scenario, which is due to the lower emission tax compared to the increase in N fertilizer price. **b** NMEModerate scenario captures the SNUpE effect based on econometric estimation, while the NMEHigh scenario estimates the combined effects of high enhancement in SNUpE and MRS

Results

Impacts on N fertilizer use, N surplus, and N pollution

In the CAU scenario, N fertilizer use (N fertilizer use hereafter refers to synthetic N fertilizer use, unless otherwise specified) in China increases steadily from 34.9 to 44.9 Mt N between 2015 and 2060 (Fig. 1a). N fertilizer use intensity, measured as the ratio of N fertilizer amount used per cropland area, increases constantly, reaching 302.1 kg N/ha in 2060 (Fig. SI-5). As an indicator of potential N losses to the environment from soil, the N surplus displays a similar pattern of N fertilizer use (Fig. 2a). The N surplus intensity, measured as the ratio of the amount of N surplus to cropland area, increases rapidly from 185.5 kg N/ha in 2015 to 218.1 kg N/ha in 2025, and then remains stable between 224.8 and 233.2 kg N/ha. Under this counterfactual scenario without fertilizer policy reform, cumulative N_2O emissions from the Chinese agricultural sector could rise to 19.1 and 38.6 Gt CO_2eq by 2030 and 2060, respectively (Fig. SI-6).

N fertilizer use in the PAU scenario can be reduced by 14.4 and 13.5 Mt in 2030 and 2060, respectively, relative to the CAU scenario (Fig. 1a). Corresponding to high ambitions in the AMB scenario, N fertilizer use can be further reduced by 6.8 and 10.1 Mt in 2030 and 2060, respectively. Since the policy scenarios consist of different measures, this study further disaggregates the effects to a set of sub-scenarios. Compared to the CAU, improving SNUpE and manure recycling share to cropland (NMEHigh) can lead to the largest reduction in fertilizer use by 21.7 Mt N in 2060, followed by a moderate improvement in nutrient management efficiency (NMEModerate) and a nitrogen taxation scheme (NitrogenTax) with respective reductions of 13.4 and 9.8 Mt N fertilizer (Fig. 1b). The FMS removal alone has a limited effect on reducing N fertilizer use with 1.6 Mt. This is related to the low-price elasticity of fertilizer demand, a measure of the response of changes in fertilizer use to

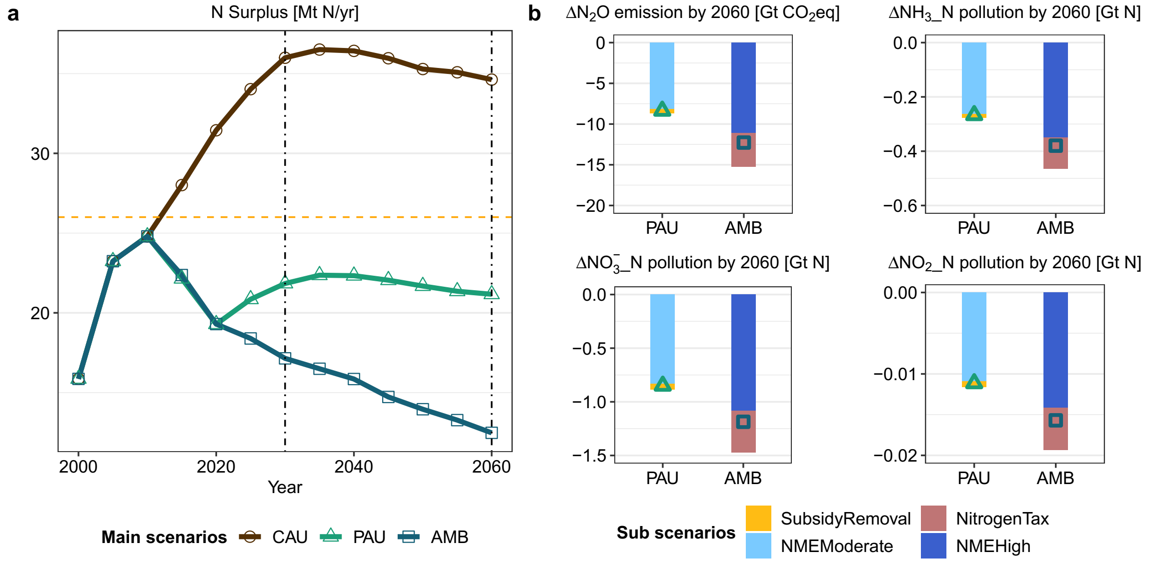

Fig. 2 **a** N surplus between 2000 and 2060 across three main scenarios: the dashed yellow line represents China's regional nitrogen planetary boundary. **b** Changes in cumulative N pollution in terms of N_2O, NH_3–N, NO_3^-–N, and NO_2–N by 2060 across the main and corresponding sub-scenarios relative to those in the CAU scenario

changes in prices, based on our sensitivity analysis of fertilizer prices (Fig. SI-8).

The reduction in N fertilizer use leads to lower N surplus and pollution. The N surplus dynamics are similar to the N fertilizer use pattern, with the largest reduction of 22.1 Mt in 2060 in the AMB scenario, compared to the CAU scenario (Fig. 2a). Our results show that with the current measures in the PAU scenario and further efforts in the AMB scenario, the nitrogen surplus can be kept well below the country's N planetary boundary–26 Mt (Chang et al. 2021) (Fig. 2a), which indicates a safe operating boundary of human activities without damaging the functioning of resilience of the earth system, and is conducive to human welfare (Steffen et al. 2015). Fertilizer use intensity under the PAU and AMB scenarios in 2060 is reduced by 29.7% (89.7 kg N/ha) and 53.4% (161.4 kg N/ha) relative to the CAU in 2060, respectively (Fig. SI-5), and the N surplus intensity is further reduced by 38.6% (89.9 kg N/ha) and 64.6% (150.7 kg N/ha), respectively.

The model results indicate that N pollution can be reduced under the PAU and AMB scenarios, while the reduction rates of individual N pollutants differ between the scenarios. The cumulative N_2O emissions in the AMB scenario can be reduced by 31.8% in 2060, 1.5 times as those in the PAU scenario (Fig. 2b). Similarly, the reductions in ammonia (NH_3), NO_2 emissions, and nitrate (NO_3^-) in the AMB scenario are larger than that in the PAU scenario (Fig. 2b). The reduction in cumulative N_2O emissions in the period of 1995–2060 ranges from 1.4 to 28.7%, depending on specific policies or measures. Among the sub-scenarios considered in this study, the NMEHigh is the most effective in reducing N_2O emissions by 28.7%, followed by NMEModerate, NitrogenTax, and SubsidyRemoval (Fig. 2b). The results of NH_3, NO_3^-, and NO_2 are consistent with N_2O emissions. This is reasonable, as improving NME can directly reduce the fertilizer use, which is the main emission source of the N pollutants. However, only the N_2O emission in the NitrogenTax scenario is taxed, while the NH_3, NO_3^-, and NO_2 (the additional pollutants of synthetic reaction) are reduced in an indirect way. It is worth noting that the overall abatement effect of N emission is smaller than the sum effects of the individual measures, which indicates that individual abatement effects partly offset each other.

Impacts on food prices, food self-sufficiency, and productivity

While our model results indicate that China's fertilizer policies are effective in reducing N fertilizer use and mitigating N surplus and pollution, food security impacts may differ across different measures. Food prices are projected to decline over time in the CAU, PAU, and AMB scenarios. The differences in food prices between the PAU and CAU scenarios are marginal, because the negative impacts of the abolition of the fertilizer subsidy are neutralized by higher NME. Compared with CAU, food prices in the SubsidyRemoval scenario increase by 1.2% due to lower agricultural production in 2060, while it decreases by 1.0% associated with higher agricultural production in the NMEModerate scenario. However, the food prices in the AMB scenario in 2030 and 2060 are, respectively, 13.7% and 13.8% higher than those in the CAU counterpart (Fig. 3a), which is

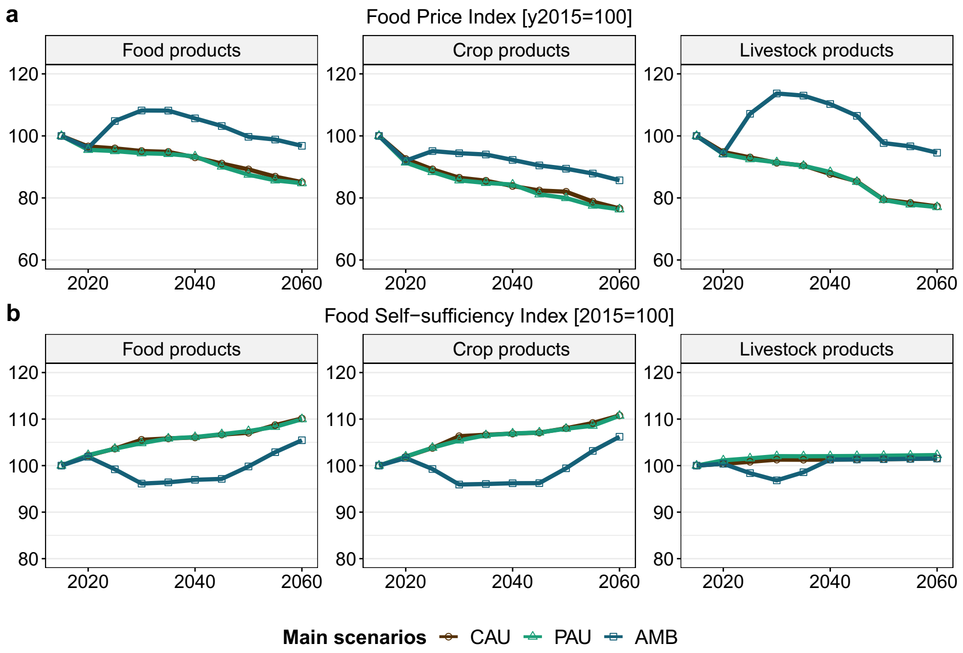

Fig. 3 Food price index (**a**) and self-sufficiency index (**b**) in China. Food products represent all agricultural products, including crop and livestock products. Crop products include cereals, oil crops, oil palm, roots/pulses, and sugar. Detailed production activities are shown in Table SI-1. The differences in food prices between the PAU and CAU scenarios are marginal and are shown as overlapped in the graph

related to the exorbitant price caused by the nitrogen tax (20.3% higher in 2030 and 22.8% higher in 2060 relative to the CAU). For the livestock products, the changes in food prices between the AMB and CAU scenarios are 24.5% and 22.4% in 2030 and 2060, two times higher than that of food crop products. The drop in prices of livestock products in the AMB scenario after 2030 is related to an improvement in management efficiency of nutrients, which partly offsets the effect of the nitrogen tax on food prices. Within the food crop products, there are large variations in price changes under these two scenarios compared with the CAU scenario, with prices of staple food crops changing from − 3.8 to 36.4% during 2020–2060, while the prices of oil crops change from − 1.5 to 11.0% in the same period.

Food self-sufficiency is another aspect of food security, about which the Chinese government is highly concerned. Food self-sufficiency is measured here as the ratio of domestic food production to demand. Under the CAU and PAU scenarios, China's food self-sufficiency is expected to increase by 10.1% over the period 2015–2060, whereas a slight decrease of 8.7% in self-sufficiency in 2030 and 4.0% in 2060 is expected in the AMB scenario, compared to the CAU (Fig. 3b). Changes in the self-sufficiency for livestock products are relatively small, with the largest change being a decrease of 4.4% in 2030 under the AMB scenario (Fig. 3b).

As the underlying factor of food self-sufficiency, this study focuses on the net trade patterns of main crops, such as cereals, oil crops, and livestock products, which play important roles in human nutrition (Wang et al. 2016). Under the CAU scenario, China is projected to be a net exporter of cereals after 2025, and a large net importer of oil crops (e.g., soybeans). For livestock products, the net imports are relatively small, while pigs are the major import products. The model results indicate that the net trade of these three

Table 2 Relative changes in land-use intensity, average yields and N productivity with respect to the levels in 2015 [%]

	Year	CAU	PAU			AMB		
			Overall effect	Sub-scenarios		Overall effect	Sub-scenarios	
				SubsidyRemoval	NMEModerate		NitrogenTax	NMEHigh
Land-use intensity	2030	16.1	15.3	14.0	16.1	10.2	8.5	16.3
	2060	17.0	17.2	15.9	17.0	11.0	8.5	17.2
Average yields	2030	22.6	22.3	19.5	23.7	12.1	11.5	24.1
	2060	28.0	28.8	24.8	27.7	18.3	15.1	28.2
N productivity	2030	0.5	21.1	2.0	22.1	37.0	4.7	33.2
	2060	− 0.3	18.5	− 0.3	19.2	66.1	2.7	62.6

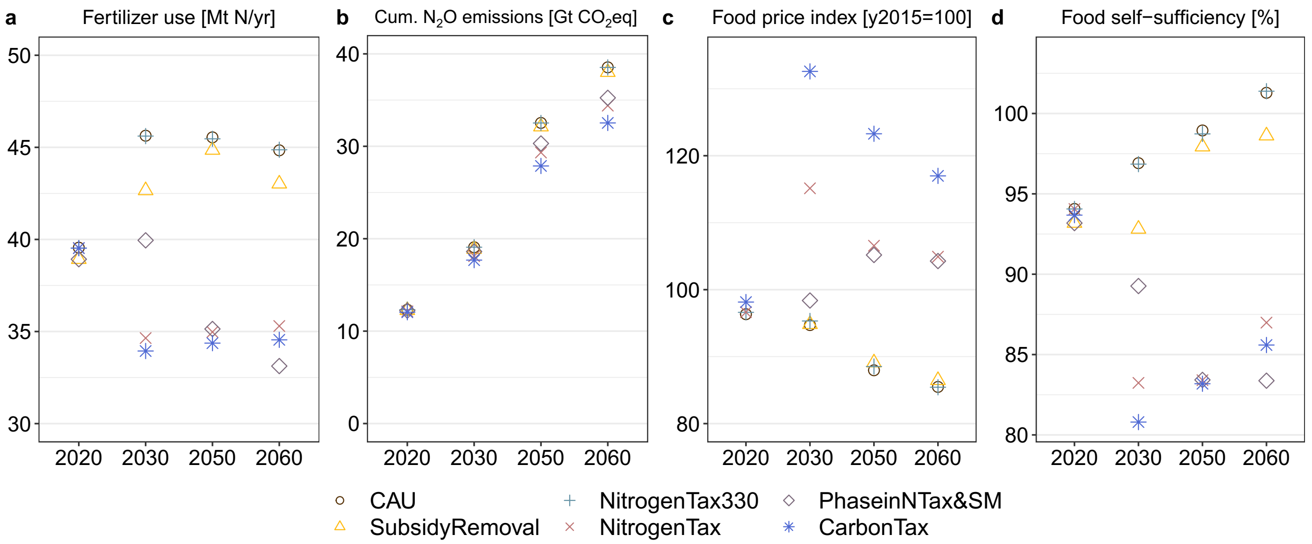

Fig. 4 Environmental and economic impacts of the FMS removal and emission taxation schemes. PhaseinNTax&SM scenario is the combination of SubsidyRemoval and phase-in nitrogen tax starting at 2025. In the NitrogenTax330 scenario, a nitrogen tax is imposed in China after 2015 at the price of 330 USD/ton N, which is the same as the increase of fertilizer price if fertilizer manufacturing subsidies are abolished

products would not be greatly affected under the PAU scenario. However, under the AMB scenario, China is expected to increase net imports of cereal and livestock products by 96.0 Mt and 3.8 Mt in 2030, respectively, compared to the CAU scenario (Fig. SI-7). The net imports of soybeans in these two scenarios are similar with those in the CAU scenario, especially in the short term.

This study considers three productivity metrics, i.e., land-use intensity, average yields, and N productivity. Land-use intensity in China increases by 16.1% between 2015 and 2030 in the CAU scenario and remains constant afterwards. The overall growth rates of land-use intensity and average yields in the PAU and AMB scenarios are lower than those in the CAU during this period. Broken down by sub-scenarios, the results indicate that improvement in NME is a decisive factor, driving higher crop productivity growth rates, while the FMS removal and imposition of nitrogen tax per se could lead to lower productivity growth (Table 2). Compared to the changes in land-use intensity and average yields, changes in N productivity (i.e., the ratio of calorie contained in food crops to the amount of N fertilizer used) are higher in both PAU and AMB scenarios than the CAU scenario. It is worth noting that FMS removal and a nitrogen taxation scheme could reduce crop productivity in terms of land-use intensity and average yields, with the latter having a larger negative impact. Improving SNUpE or combining with increasing manure application can offset negative impacts of FMS removal and a nitrogen taxation scheme on land-use intensity and average yields, and can lead to large increases in N productivity.

Complementary analysis of N cost effect on the environment and food security

A subsidy removal policy is equivalent to imposing taxation on the input side, while a GHG tax imposes a tax on undesirable output. Previous results show marginal reduction effects in the SubsidyRemoval scenario. Therefore, we further investigate the effectiveness of mitigation and economic responses with respect to FMS removal and different types of GHG taxes. Model results indicate that emission taxation schemes can lead to less N fertilizer use (Fig. 4a), while the subsidy removal policy is more effective in fertilizer reduction when considering the costs. The N fertilizer reduction per unit cost in the SubsidyRemoval scenario is 241.8 kg N/USD in 2030, three and eight times that of the nitrogen tax and carbon tax scenarios, respectively (Table SI-6). Imposing an emission tax is more effective for controlling N_2O emissions than removing fertilizer subsidies (Fig. 4b). Within the emission taxation schemes, the carbon tax is more effective at reducing overall GHG emissions, while the nitrogen tax only affects nitrogen-related emissions. However, GHG taxation schemes could lead to higher food prices and lower self-sufficiency, while removing fertilizer subsidies has marginal impacts on food security (Fig. 4c, d). Phasing in nitrogen tax in a stepwise manner in combination with FMS removal (PhaseinNTax&SM) appears to

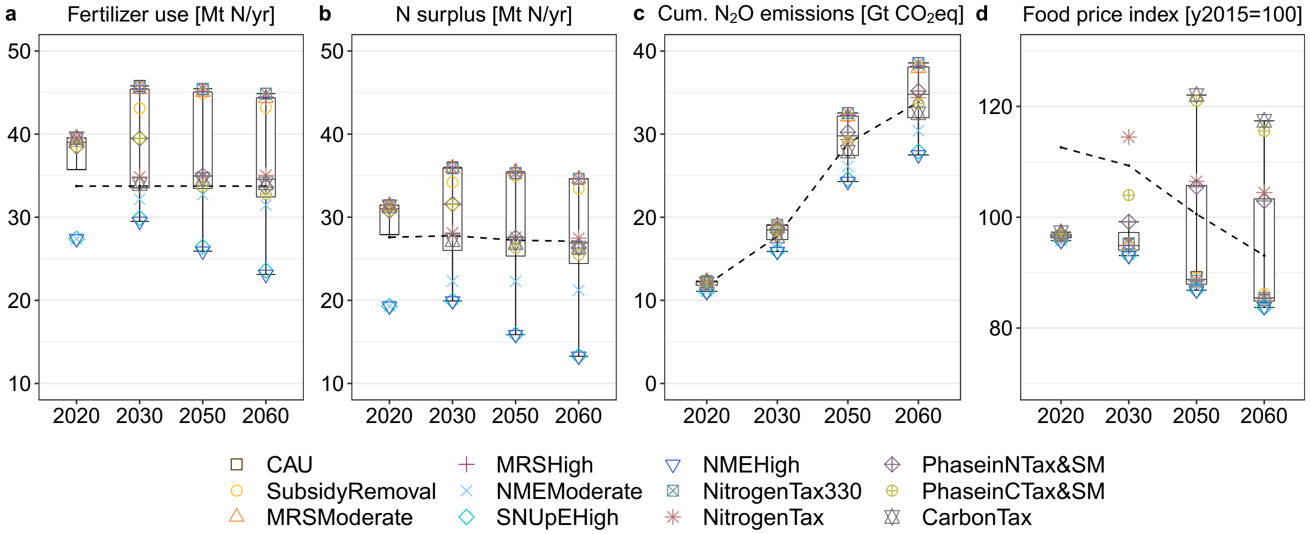

Fig. 5 Impacts of all the policy sub-scenarios including SubsidyRemoval, SNUpE, MRS, NME, and GHG emissions taxes. Dashed lines represent the results of the "Zero Growth Strategy"

slow the rapid increase in food prices in the short term while achieving similar effects for mitigating N pollution (Fig. 4).

Sensitivity analysis of fertilizer prices

To further understand how N fertilizer use varies with respect to the FMS removal policy, we conduct a sensitivity analysis with fertilizer prices ranging from 720 to 1050 USD/ton N with an incremental interval of 30 USD/ton N. The model results show that there is a nonlinear relationship between the amount of N fertilizer use and fertilizer prices, particularly after 2050 because of the relatively low N fertilizer used amount (Fig. SI-8). The model results also show that the price elasticity of fertilizer demand is relatively low, on average 4.2%. The largest difference of N fertilizer use across different fertilizer prices in any single year is 4.1 Mt N. Similarly, the impact of increasing fertilizer prices on mitigating N_2O emissions is relatively marginal, ranging from 0.3 to 2.9% in 2015–2060, compared with the CAU scenario.

To assess the feasibility of meeting the target set in the "Zero Growth Strategy" in the long term, we try to analyze the individual and synergistic effects of all the single and combined measures. The results indicate that the gaps between CAU indicator values and the targets in the "Zero Growth Strategy" can be closed in the long term, especially in scenarios with high SNUpE (Fig. 5a). In the most ambitious scenario (high enhancement in nutrient management efficiency, NMEHigh), N_2O emissions, fertilizer use, and N surplus decrease by 28.7%, 48.5%, and 61.7%, respectively, compared to those in the CAU in 2060, without resulting in higher food prices at the same time.

Discussion

By using the agro-economic land system model (MAgPIE) coupled with an econometric method, this study provides a forward-looking assessment on the impacts of China's fertilizer policy reform, which consists of the removal of fertilizer manufacturing subsidies and measures associated with improving agricultural nutrient management efficiency. Our results reveal that enhancing soil N uptake efficiency and MRS alongside fertilizer subsidy removal can largely reduce N fertilizer use and N losses and abate N pollution in the short and long term, while food security remains largely unaffected.

Comparison with other studies and uncertainty

Our model results are consistent with other studies. For instance, van Wesenbeeck et al. (2021) show that synthetic fertilizer use can be reduced by 30% by 2030 without negatively impacting food self-sufficiency if measures of improving NUE, increasing the use of organic fertilizer, and promoting the program of soil quality measurement are taken on the ground. Gu et al. (2017) argue that lower NUE led to lower self-sufficiency from the 1980s to 2010 in China, which supports our result by indicating that higher NUE can ensure food security. By reforming fertilizer policies to improve NME, average crop yields can be increased by 1.4% by 2030, while fertilizer use can be decreased by 29.8%. The effects are lower than those from field experiments that focus on maize, rice, and wheat and enhanced management practices (Chen et al. 2014; Cui et al. 2018). The discrepancy could be due to our estimation about the whole agriculture sector and our consideration of changes in the cropping pattern and food demand. Our results confirm the findings that there is high potential for China to achieve higher yields with lower pollution through sustainable intensification such as integrated soil-crop system management (Foley et al. 2011; Chen et al. 2014).

Substantial progress toward N_2O emissions mitigation can be made by reforming China's fertilizer policies in the short and long term. Agriculture contributes to 7% of the total GHG emissions in China and agricultural activities are the key sources of non-CO_2 emissions (Jin et al. 2021a; Liang et al. 2021), which are responsible for 60% of the total N_2O emissions in China (National Communication on Climate Change in China 2018). While there is an emphasis on abating CO_2 emissions (The Food and Land use Coalition 2019), exploring pathways for mitigating N_2O is also needed. Our study provides insight into feasible mitigation options of N pollution including not only N_2O but other N pollutants with marginal adverse effects on food security. Taken together, fertilizer policy reform in China can help reduce N fertilizer use and N pollution without harming food security, which could have profound implications for sustainable development goals (SDGs) including "clean water and sanitation", "climate action" and "zero hunger" (Soergel et al. 2021).

Among the measures in the policy reform, enhancing SNUpE improvements is imperative to reducing N surplus and mitigating N pollution, which is in line with the conclusions of Chang et al. (2021) and Gu et al. (2017). Our estimate of N surplus reduction by increasing SNUpE in China is 19.4 Mt N in 2050, comparable with the global level estimated (58.0 Mt) by Bodirsky et al. (2014), when considering China's share of global synthetic fertilizer consumption and the initial SNUpE setting in our model. Unlike the NUE estimates in previous studies (Gu et al. 2015; Zhang et al. 2015), SNUpE in this study is calculated based on almost all detailed sources of N flows, leading to higher magnitudes of SNUpE compared to NUE in China. Moreover, the target of "Zero Growth Strategy" can be achieved when implementing a combined scenario with higher SNUpE levels while maintaining an increase in average yields. This point also supports the findings of Wuepper et al. (2020) that national governments could reduce global nitrogen pollution without sacrificing much agricultural production.

Policy implications

Policy matters, especially when it comes to the correction of policy distortion related to fertilizer use (Gu et al. 2015; Wu et al. 2018; Kanter et al. 2020; Wuepper et al. 2020). Greening the subsidy by incentivizing the adoption of more efficient fertilizer and agricultural production technologies and practices, and facilitating best-practice adoption through farmers organizations (e.g., agricultural cooperatives) also have positive impacts on farming performance (Laborde et al. 2021; Lin et al. 2022a). Combined with the estimates of the impacts of fertilizer policy reform on SNUpE and N fertilizer prices, our simulation results based on the agro-economic land system model indicate that correcting policy distortion can effectively reduce N fertilizer use and N surplus.

Policies that simply increase fertilizer price may have limited impacts, but repurposing subsidies with broader measures could provide multiple benefits in terms of N emission reduction, food security, and climate-resilience of production (Laborde et al. 2021). In accordance with the perspective of Kanter et al. (2020) about expanding nitrogen pollution policies beyond farmers to encompass actors across the entire agri-food chain, we not only provide the first modeling evidence about the impacts of removing the FMS, but also demonstrate large and positive impacts of overall reform of fertilizer policies. It is worth noting that China's fertilizer policy reform is a successful case study for meeting environmental targets while safeguarding food security. From a global perspective, shifting the agricultural subsidies toward stimulating SNUpE appears to be a cost-effective option for sustainable development in agriculture. Down to the farm level, farmers' responses and decisions are the key elements to the success of policy reform. A series of measures have been used to incentivize farmers to reduce the amount of synthetic fertilizer use, such as providing organic fertilizer subsidies and popularizing environmental protection knowledge. More effective measures must be designed and explored to enable policymakers and researchers to increase the responsiveness of farmers to the policies. Our analysis also provides evidence for the impacts of fertilizer price changes on the production side, especially the manner in which the current fertilizer price increases rapidly due to rising raw material prices and energy prices. For example, natural gas price volatility has incited current fertilizer spikes in Europe. Furthermore, the results also provide important policy implications for other developing countries such as India and sub-Saharan Africa countries, which are still subsidizing the fertilizer industry (Takeshima 2015; Praveen et al. 2017).

In the context of achieving climate neutrality, our results of imposing a tax on the emission side indicate unavoidable higher food prices, which amounts to an increase in producer welfare benefits and the loss of consumer welfare benefits in the food market. If a mitigation policy aims to simultaneously maintain food prices, a combination of phase-in tax and fertilizer price policies could be a good measure, as shown in our complementary analysis. Moreover, producers' losses due to taxes should also be considered given that producers cannot roll over prices to the consumers because of international trade in an open economy. In addition, China has millions of smallholder farmers with vulnerable livelihoods. Hence, a compensation mechanism for producers combined with nitrogen taxation may be a suitable instrument that coordinates the welfare benefits of all stakeholders while realizing environmental goals (Gu et al. 2021).

A few caveats need to be borne when interpreting the results. First, with regard to the study design, neither the transaction costs and labor costs of improving SNUpE and MRS, nor the specific measures related to enhancing SNUpE and MRS are considered in our model, preventing us from accurately evaluating the costs and benefits of fertilizer policies. However, it has been shown that the effects of these costs are comparatively marginal compared to other types of production costs (Wang et al. 2017). The changes in labor costs due to different nutrient management practices are partly reflected by the changes in production factors requirement costs. Model results indicate that higher production factor costs are associated with higher SNUpE/MRS (Table SI-7). This implies that more organic fertilizer can result in higher labor costs on the farm, which is consistent with the existing literature (Klonsky 2011; Hörner and Wollni 2022). Additionally, although we do not consider specific measures such as slow-release fertilizers and fertigation (Zhang et al. 2015), this study uses a state-of-the-art economic method with country-representative farming data to provide evidence on changes of N inputs and outputs to estimate the joint effects of removing FMS and field management measures endorsed by the "Zero Growth Strategy" on SNUpE. Hence, our estimate can still provide strong and important evidence on fertilizer policy impacts even if transaction costs and specific measures of enhancing efficiency are not included in the model. Second, our model assumes a fertilization equivalence between N from synthetic fertilizer and N from manure, while in reality it is easier to dose synthetic fertilizer appropriately to achieve a higher NUE. Over long periods, manure can help build up soil organic matter and thereby also facilitate to achieve better absorption capacities for N inputs. Third, the estimation of the increase in N fertilizer price induced by removing FMS is based on a simple estimation due to limited data availability. This might bias the estimation of FMS removal impact on the fertilizer price and cascade the bias into the modeling results. To address this caveat, we conduct a sensitivity analysis with the fertilizer prices ranging from 720 to 1050 USD/ton N to understand how the sensitivity of the results interacts with this parameter, which indicates small differences in the results.

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Author contributions XW and BLB developed the research idea. XW, MX, and BL conducted the analysis. XW, MX, BL, and JX contributed to the writing and editing of the manuscript. All authors critically reviewed the manuscript and agreed on the final version. JPD, BLB, MS, XW, HLC, and AP developed the MAgPIE model.

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