Supplementary information (SI) for

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

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This PDF file includes:

SI-1. MAgPIE model structure

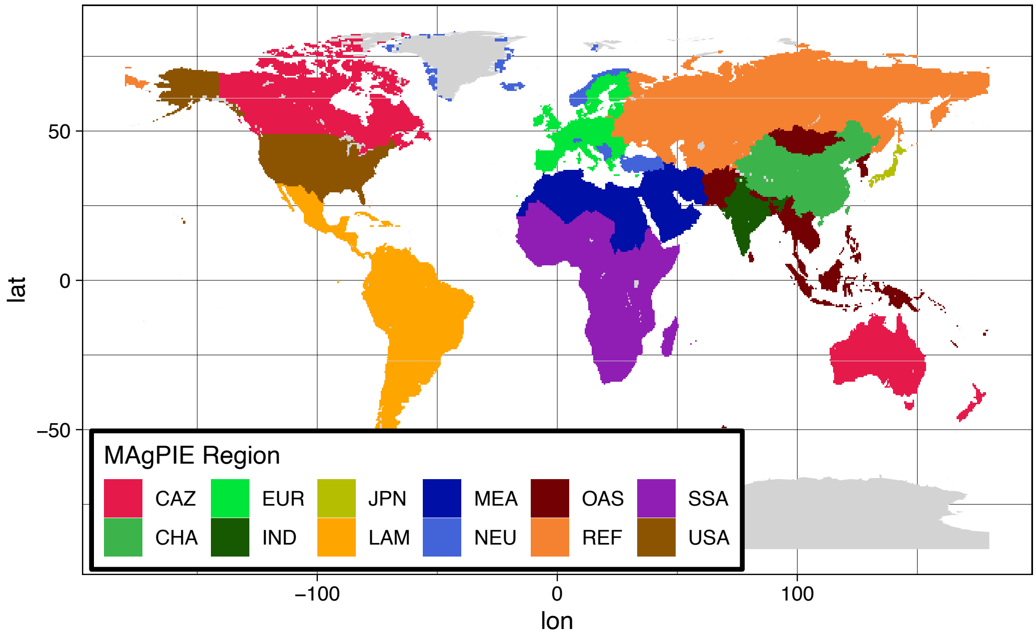

Fig. SI-1. World regions in MAgPIE. CAZ: Canada, Australia and New Zealand; CHA: China; EUR: European Union; IND: India; JPN: Japan; LAM: Latin America; MEA: Middle East and North Africa; NEU: non-EU member states; OAS: other Asia; REF: reforming countries; SSA: Sub-Saharan Africa; USA: the United States.

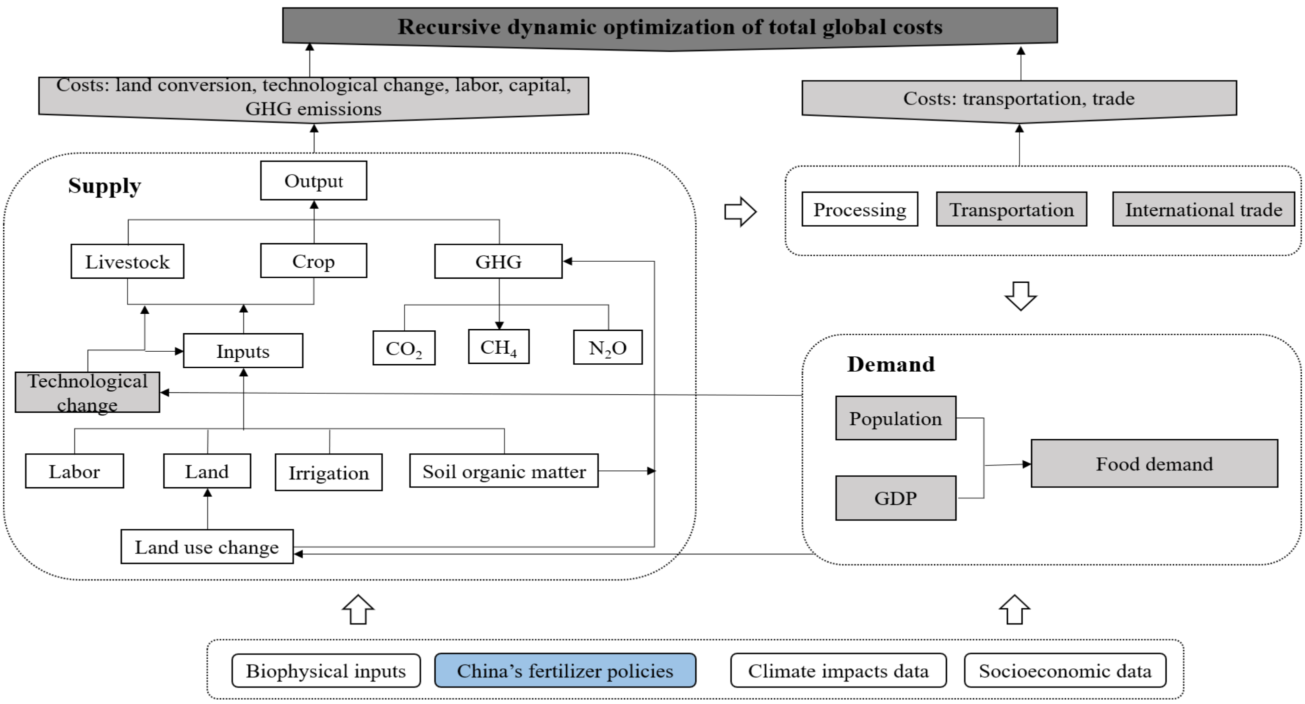

Fig. SI-2. Framework adapted from Humpenöder et al. (2015). Grey shaded areas indicate the spatial resolutions: dark grey (global), light grey (world regions), and white (cellular level). Blue shaded area indicates China's fertilizer policies shock.

Table SI-1. Production activities in MAgPIE.

Categories	Production activities
Cereals	Temperate cereals; maize; tropical cereals; rice
Oil crops	Soybean; rapeseed; groundnut; sunflower
Oil palm	Oil palm
Roots/pulses	Pulses; potato; cassava
Sugar	Sugar beet; sugarcane
Veg/fruits	Vegetables; fruits; nuts (one category)
Other	Fodder; fiber
Livestock	Ruminant meat; pork; chicken; eggs; milk

SI-2. Econometric estimations

SNUpE calculation

Soil N uptake efficiency (SNUpE) is a regional model parameter, measured as the total N outputs divided by N inputs, that reflects the fertilization technology of farmers under certain climatic and biophysical conditions (Bodirsky et al. 2014). The N flow module is an important part that links agriculture and the environment by transforming all biomass flows into N flows in MAgPIE. To maintain the N balance in the agro-environmental system, we employ the N budget approach from MADRaT (May All Data be Reproducible and Transparent) (Dietrich et al. 2021) and mrcommons (MadRat commons Input Data Library) (Bodirsky et al. 2020) and have a consistent connection of all detailed sources of N flows released from FAOSTAT (Bodirsky et al. 2012), such as N release, inflows, and fixation, which are derived from cropland soils, agricultural production, livestock feeding, manure management, and the household sector (Dietrich et al. 2019).

N outputs include N in harvested crops ($N^{harvest}$), aboveground (N^{ag}), and belowground (N^{bg}) crop residues but exclude N in seeds (N^{seed}) and N fixation within crops ($N^{fixzation\_crop}$). Specifically, the N biological fixation within crops is estimated based on the N derived from atmospheric fixation, while the remaining four components are estimated according to crop-specific production functions and their related N contents.

The total N inputs estimated in MAgPIE are classified into eight components, covering all sources of agricultural N inflows. N derived from biological fixation by free-living bacteria ($N^{fixzation\_freeliving}$) is estimated as the plant-specific share of N fixation per cultivated area multiplied by crop area. The N derived from the uptake of soil organic matter from plants (N^{som}) is measured based on land-use changes, microelements of natural soils, and climate-specific rates of soil nutrients loss under a certain cropland management system. It is assumed that all belowground crop residues are recycled into soil ($N^{bg\_recycling}$), while the remaining aboveground residues are recycled in fields ($N^{ag\_recycling}$) after they are used for livestock feed and burned in fields (N^{ag_ash}). N inflows can also originate from atmospheric deposition ($N^{deposition}$), which is estimated based on climate-specific deposition rates. Moreover, N derived from manure (N^{manure}) and synthetic fertilizer ($N^{fertilizer}$) can be calculated based on a given animal waste management system and fertilization technology level, respectively. In this study, we assume that there is no difference in the fertilizer equivalences between manure and synthetic fertilizer.

Compared with other calculations for nitrogen use efficiency (Gu et al. 2015; Zhang et al. 2015), our estimation of SNUpE is slightly higher as we consider almost all detailed sources of N flows. Hence, the measure of SNUpE is as follows.

$$N^{output} = N^{harvest} - N^{seed} + N^{ag} + N^{bg} - N^{fixzation\_crop}$$

$$N^{input} = N^{fixzation\_freeliving} + N^{som} + N^{bg\_recycling} + N^{ag\_recycling} + N^{ag\_ash} + N^{deposition} + N^{manure} + N^{fertilizer}$$

$$SNUpE = \frac{N^{output}}{N^{input}}$$

DID estimation on soil N uptake efficiency

Table SI-2. Impacts of Chinese fertilizer policies on synthetic fertilizer use based on DID estimation.

	(1)	(2)	(3)	(4)	(5)
Fertilizer policies	-0.085**	-0.066*	-0.106***	-0.153***	-0.155*
	(0.039)	(0.037)	(0.041)	(0.071)	(0.082)
County fixed effect	YES	YES	YES	NO	NO
Year fixed effect	YES	YES	YES	YES	YES
Year-county fixed effect	NO	YES	YES	NO	YES
Control variables	NO	NO	YES	YES	YES
Household fixed effect	NO	NO	NO	YES	YES
Observation	6,568	6,568	5,301	5,301	5,301

Note: Household and farm characteristics, such as age, health, and education of household head, growing preference, cropping experience, farm size, land fragmentation, family labor, technical training, rice production subsidy, agricultural insurance, and technologist service are controlled. Standard errors are shown in parentheses. *** $p < 0.01$. ** $p < 0.05$. * $p < 0.1$.

Table SI-3. Impacts of Chinese fertilizer policies on rice yields based on DID estimation.

	Yields
Fertilizer policies	0.080***
	(0.031)
Year fixed effect	YES
Year-county fixed effect	YES
Control variables	YES
Household fixed effect	YES
Observation	5,300

Note: Household and farm characteristics, such as age, health, and education of household head, growing preference, cropping experience, farm size, land fragmentation, family labor, technical training, rice production subsidy, agricultural insurance, and technologist service are controlled. Standard errors are shown in parentheses. *** $p < 0.01$. ** $p < 0.05$. * $p < 0.1$.

Estimation of changes in N fertilizer price

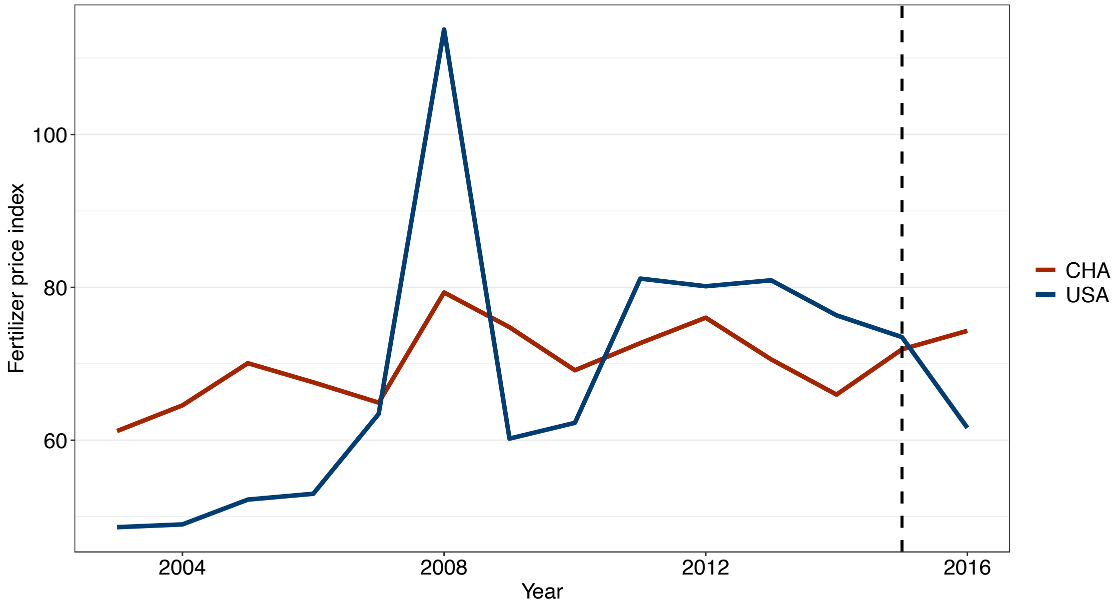

Fig. SI-3. Fertilizer prices in China and the USA in 2003-2016. Data are obtained from USDA and QianZhan Database. Increases in the fertilizer price in the USA in 2008 were largely driven by high energy prices and high input costs.

SI-3. Scenario specifications

Table SI-4. Scenario specifications for the complementary analysis.

Scenarios	Description
Taxation	NitrogenTax: A nitrogen tax imposed on N_2O emission in China from 2015. NitrogenTax330: A nitrogen tax is imposed on N_2O emission in China after 2015 at the price of 330 USD/ ton N, the magnitude of which is the same as the increase of fertilizer price if fertilizer manufacturing subsidies are abolished. CarbonTax: A carbon tax imposed on CO_2, CH_4, and N_2O emissions in China from 2015.
PhaseinNTax&SM	SubsidyRemoval in combination with Phase-in nitrogen tax starting in 2025.
PhaseinCTax&SM	SubsidyRemoval in combination with Phase-in carbon tax starting in 2025.

Table SI-5. Scenario specifications for the sensitivity analysis.

Scenarios	Description
Nutrient Management Efficiency (NME)	SNUpEModerate: SNUpE improves to 0.52 in 2015 and 0.58 in 2020, and after that it remains constant. SNUpEHigh: SNUpE here is the same as that in SNUpEModerate before 2020, and after that it increases to 0.69 in 2060. MRSModerate: Moderate enhancement in MRS. MRSHigh: High enhancement in MRS. NMEModerate: Combination of moderate enhancement in SNUpE and low enhancement in MRS scenarios. NMEHigh: Combination of high enhancement in SNUpE and high enhancement in MRS scenarios.
Fertilizer Price	Fertilizer prices range from 720 to 1050 USD/ton N with an incremental interval of 30 USD/ton N.

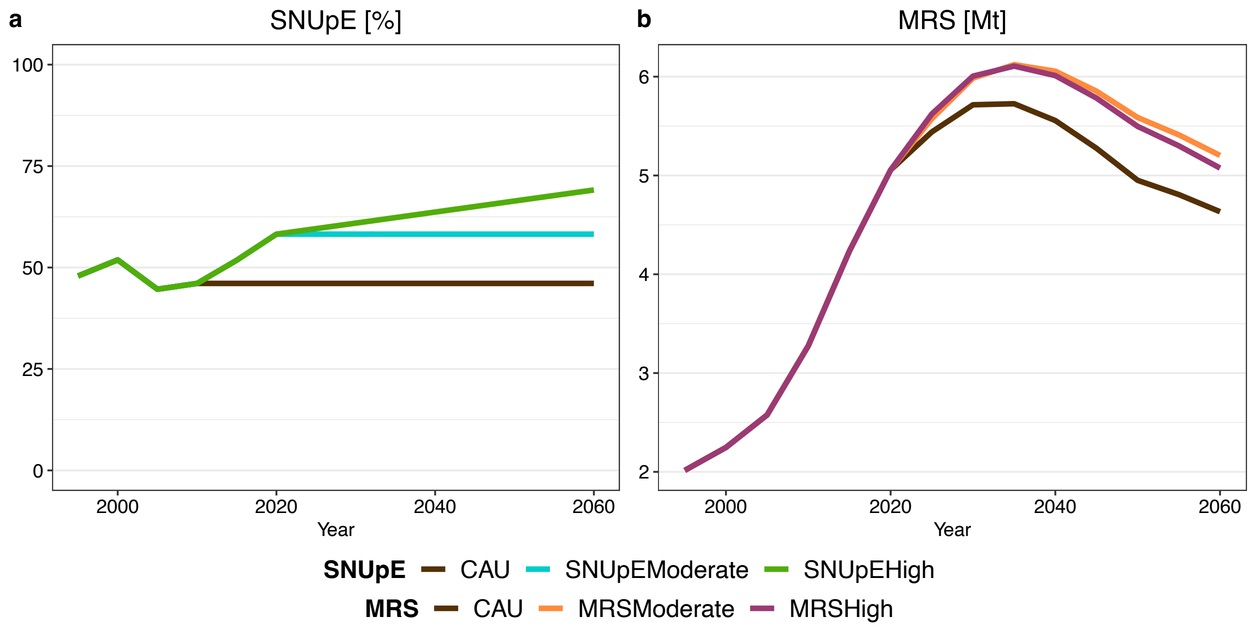

Fig. SI-4. Development of SNUpE (panel a) and MRS (panel b) over time. The values of manure recycled to soil in MRSHigh scenario are slightly lower than those in the MRSModerate scenario after 2030, which is associated with changes in the structure of food demand in China.

SI-4. Additional model results

Figures

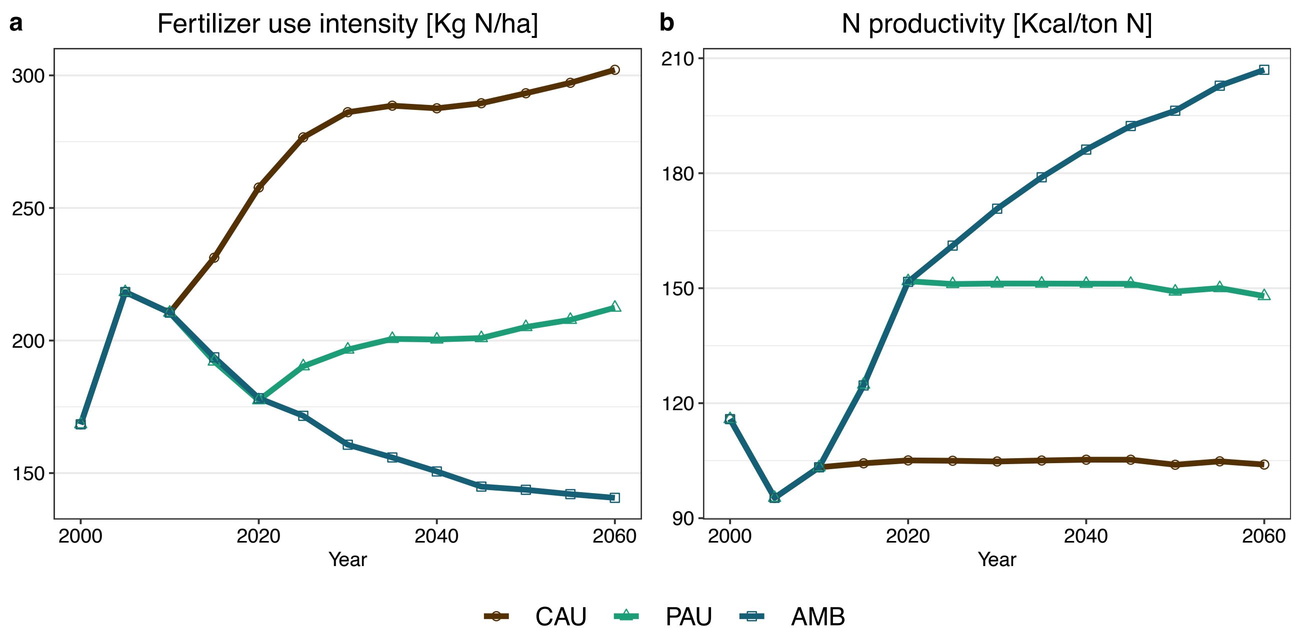

Fig. SI-5. Fertilizer use intensity (panel a) and N productivity (panel b) from 2000 to 2060 across CAU, PAU, and AMB scenarios. Fertilizer use intensity is measured by the ratio of fertilizer used amount to cropland area. N productivity is measured by the ratio of calories contained in food crops to N fertilizer used amount.

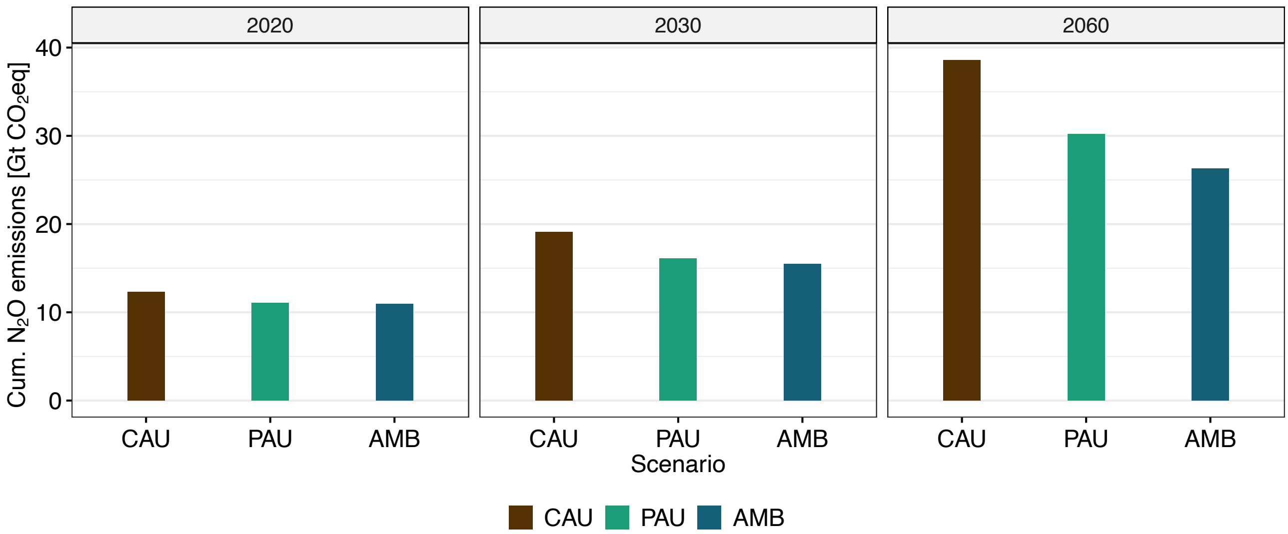

Fig. SI-6. Cumulative N_2O emissions across CAU, PAU, and AMB scenarios in periods of 1995-2020, 1995-2030, and 1995-2060.

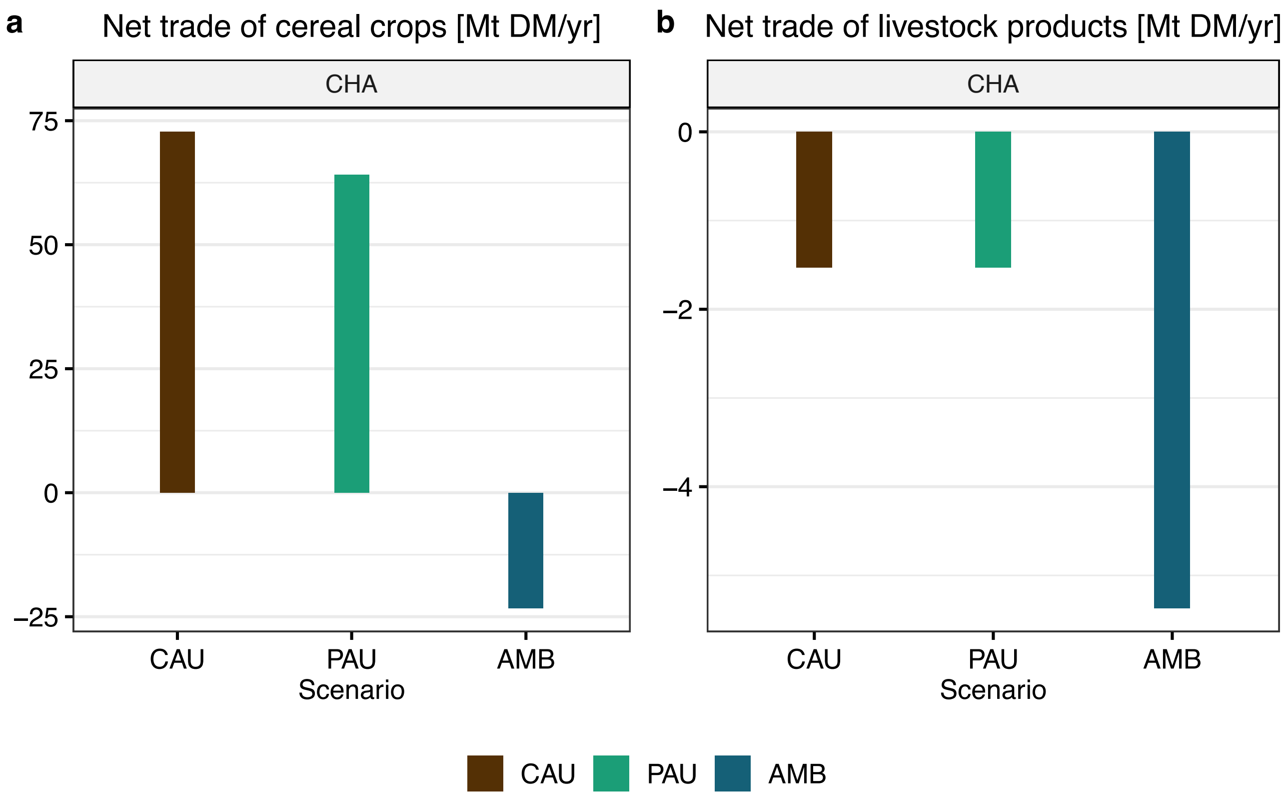

Fig. SI-7. Net trade of cereal crops (panel a) and livestock products (panel b) in 2030 across the CAU, PAU, and AMB scenarios. Negative values refer to the net imports.

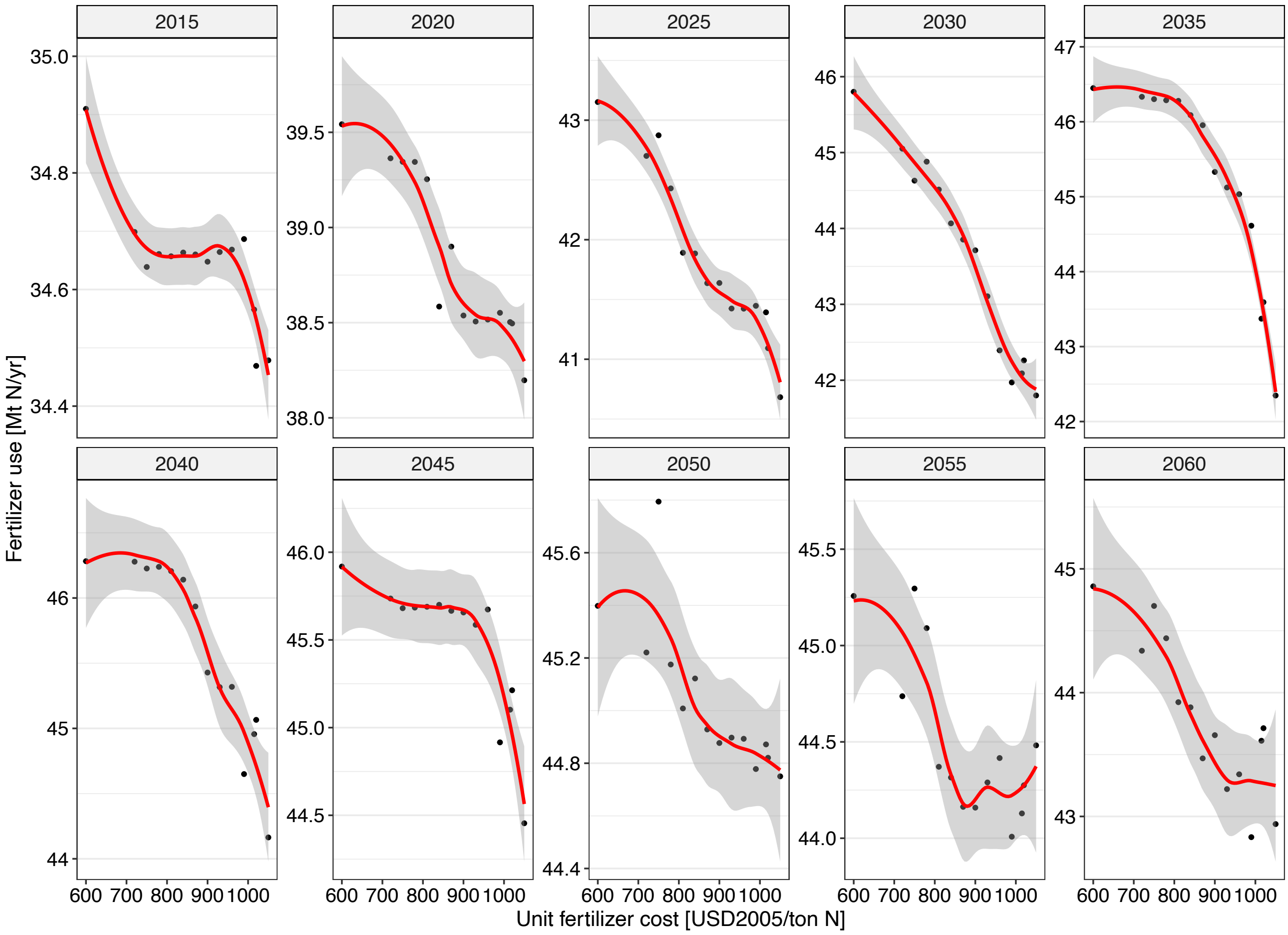

Fig. SI-8. Correlation between N fertilizer used amount and fertilizer price from 2015 to 2060. The red lines represent the fitted lines of N fertilizer used amount and fertilizer price.

Tables

Table SI-6. N Fertilizer reduction per unit cost [kg N/USD] in 2020-2060 under SubsidyRemoval and GHG taxation scenarios relative to the CAU scenario.

Year	SubsidyRemoval	NitrogenTax	CarbonTax
2020	-50.3	-4.9	-2.4
2030	-241.8	-73.0	-31.9
2040	-71.8	-77.8	-36.4
2050	-47.9	-75.1	-36.3
2060	-138.6	-73.7	-37.8

Table SI-7. Annual production factor costs for crop production across CAU and SNUpE scenarios in China in 2020-2060 [mio. USD05MER].

Year	CAU	SNUpEModerate	SNUpEHigh
2020	348708.5	348982.0	348982.0
2025	348175.7	348902.1	348932.8
2030	340978.7	342471.3	342659.3
2035	340509.9	341713.6	342037.2
2040	337742.5	338601.0	338616.6
2045	331914.8	332739.0	333925.2
2050	323614.9	326549.8	327519.4
2055	315073.0	316296.2	316990.5
2060	304546.5	304487.1	305699.7

Table SI-8. Cropland area across the CAU, PAU, and AMB scenarios [mio. ha].

Year	CAU	PAU	AMB
2020	153.4	154.2	153.7
2025	156.0	157.2	153.2
2030	160.1	160.0	153.2
2035	161.0	160.6	154.0
2040	160.9	160.7	156.0
2045	158.6	159.0	154.7
2050	154.8	155.2	153.9
2055	152.3	151.4	153.4
2060	148.5	147.8	151.3

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