Supporting Information

1. Supporting Data

1.1 Agricultural employment

This dataset was constructed based on the primary dataset on labor force participation, published by the International Labor Organization (via the World Bank). The sources for this dataset are described in detail here: https://ourworldindata.org/agri-employment-sources.

1.2 Urbanization

Urban population refers to the populace residing within urban areas, delineated as per the definitions provided by national statistical offices. The data pertaining to urban populations are collected and subjected to a process of smoothing by the United Nations Population Division. This methodology entails that the classification of urban populations is contingent upon the specific criteria and parameters used by each nation's official statistical authorities to define urban regions.

1.3 Age structure

The median age serves as a pivotal point of demarcation within a population. This statistical measure partitions the populace into two equitable segments, ensuring that the number of individuals surpassing the median age is equivalent to the count of those falling below it. In essence, the median age provides an insightful perspective on the distribution of ages within a given population, offering a balanced representation of age demographics. The source of the provided information is the United Nations, World Population Prospects (2022). The data presented in this study encompasses historical estimates spanning from the year 2000 to 2021.

1.4 Gross Domestic Product (GDP) Per Capita (PGDP)

GDP per capita was based on purchasing power parity (PPP), which is gross domestic product converted to international dollars using purchasing power parity rates. It was calculated without making deductions for depreciation of fabricated assets or for depletion and degradation of natural resources. For the concept and methodology of the processes, please refer to the International Comparison Program website: https://www.worldbank.org/en/programs/icp.

1.5 Digital Elevation Model (DEM)

We used the global elevation data sets at 0.0625° grids compiled from the 15 arc-second resolution GMTED2010 global digital elevation model developed by the USGS and the NGA for global and continental scale applications [1,2]. This product suite provides global coverage of all land areas from lat 84°N to 56°S. There is no special value for ocean waters in these files; the elevation of the ocean water is simply 0 meter.

2. Supporting results and discussions

2.1 $PM_{2.5}$ premature global deaths

Millions of people die prematurely every year from diseases caused by $PM_{2.5}$

air pollution, partly associated with NH_3 [3,4]. $PM_{2.5}$ was responsible for an estimated 3.9 million premature global deaths in 2020; this included over 1.3 million deaths in China, 1.0 million in India, and over 40,000 in the US. Agriculture contributed from 1-20% of premature deaths related to $PM_{2.5}$ depending on the country, with a high percentage in the Europe Union (15-20%), China and India (10-15%) and the US (7-10%).

2.2 Impact on N deposition

Cropland N_r emissions contribute to N deposition to natural and semi-natural environments, which may lead to species loss and changes in structure and function of sensitive plants, eutrophication of terrestrial and aquatic ecosystems and nitrate in groundwater [5,6]. Global N_r deposition greatly exceeded critical levels (to limit terrestrial biodiversity loss), especially in developing countries dominated by smallholder farms, including China and India (where N_r deposition was more than double the critical limit). Total N_r deposition was mainly dominated by NH_x, with a global mean of 54%, but which accounted for more than 55% of the total in many countries such as China (63%), India (70%), Europe (including Germany, France, Spain and Poland, 56-65%). In many areas of Eastern China and Northern India, NH_x deposition exceeded 30 kg N ha^{-1} yr^{-1}, posing an increasing threat to ecosystems.

Through increasing farm optimization, NH_x deposition can be reduced by 13% (9-25%), with large decreases in China (21%), India (25%), Pakistan (15%), Myanmar (16%), and Tailand (23%), while reductions in the USA and European countries were smaller (below 5%). Correspondingly, the proportion of NH_x in total N_r deposition could be reduced by 7% in India (from 70% to 63%), 6% in China (from 63% to 57%) and Tailand (from 62% to 56%), followed by Pakistan (4%, from 69% to 65%) and Myanmar (4%, from 62% to 58%). Expanding farm size is a feasible pathway to address the issue of increasing NH_x deposion in China and India, which is 3-4 times that of large-scale farming countries (e.g., the USA and European Union).

2.3 Comparison of this study with others

Globally, our estimates of agricultural NH_3 emissions from cropping generally fall within the ranges reported by other global emission inventories (18-37 Tg N yr^{-1}) (**Table S7**). The magnitude of agricultural NH_3 emissions in 2010 in our study (28.9 Tg N yr^{-1}) closely aligns with, albeit slightly lower than, the estimate of CEDS and EDGAR (31-36 Tg N yr^{-1}) for the same year. Our estimates closely match regional emission data (**Table S7**). For instance, in China, cropping NH_3 emissions align with estimates from REAS (7.4 vs. 8.9 Tg N), CEDS (7.4 vs. 6.8 Tg N) and EDGAR (7.4 vs. 7.8 Tg N) in 2010, Zhang et al. (6.4 vs. 7.4 Tg N) in 2008. In the EU, NH_3 emissions correspond to regional estimates of Paulot et al. (2.6 vs. 2.2 Tg N) averaged over 2005-2008 and EDGAR (2.1 vs. 2.3 Tg N) in 2010, though they are slightly lower than CEDS (2.7 Tg N). Lastly, for the US, our estimates align with Zhang et al. [7] (3.0 vs. 2.9 Tg N) during 2000-2010, NEI (3.1 vs. 3.1 Tg N) in 2006.

We assessed the global status of N fluxes using the GEOS-Chem chemistry transport model based on measurements from ground-based networks in China, the USA, and Europe for the year 2010. In China, wet NH_4^+ measurements were gathered from the Nationwide N Deposition Monitoring Network (NNDMN) across 43 sites[8], covering background, farmland, and urban areas. The NADP in the USA provided wet NH_4^+ concentration and deposition data from 265 sites, while in Europe, 84 sites from the European Monitoring and Evaluation Program (EMEP) were employed for evaluation[9]. The modeled wet NH_x and NO_y exhibited a general agreement with measurements in regions with intensive monitoring sites (overall bias below 10%, **Fig. S16**).

2.4 Lessons from developed countries

The consolidation of fragmented agricultural land is a long-term process. Germany, for instance, has emphasized land consolidation since the 19th century, and even after more than a century, significant progress in addressing fragmented land was achieved only after the enactment of a dedicated "Land Consolidation Act" following World War II [10]. France, despite investing substantial administrative resources and financial funds since 1960 and establishing specialized land management institutions, continues to face challenges in consolidating agricultural land due to the evolving demands of efficient land utilization in the face of village renewal and agricultural modernization [11]. Japan, although its efforts to address fragmented land started relatively late, has also been engaged in this endeavor for decades; however, the issue of land fragmentation remains unresolved to date [12,13].

The experiences of Germany, France, the Netherlands, and Japan in managing fragmented agricultural land provide several insights that can be relevant for developing countries. First, Germany, France, and the Netherlands prioritize legislation to manage agricultural land fragmentation [14]. They have well-defined laws specifying stakeholders' rights, responsibilities, government roles, and adjusting with changing conditions. For developing countries, though existing laws touch on land issues, dedicated legislation is needed to guide and standardize efforts to address land fragmentation, drawing from foreign experiences and domestic pilots. This would establish a strong legal foundation for effective action. Second, developed nations tackled land fragmentation using land consolidation and transfers [15]. Governments led consolidation, and market-driven transfers were guided by interventions. A blend of strong government and effective market roles yielded success. Developing countries should emphasize government leadership in consolidation, while promoting consolidated land transfers to counter fragmentation in its efforts. Third, government-supported intermediary organizations are vital for efficient land fragmentation management [16]. These organizations coordinate efforts, facilitate funding, and streamline processes. While developing countries have made progress, it should enhance intermediary organization roles in both land consolidation and transfer, ensuring more effective mitigation of land fragmentation. Fourth, policies encouraging weak small farmers to leave agriculture have eased land fragmentation by offering subsidies, pensions, and incentives. Developing countries face a similar challenge with numerous small farmers, but factors like aging labor, urbanization, and improved livelihoods make transitioning feasible. Encouraging voluntary and compensated land transfer through incentives and social security can help mitigate fragmentation. Fifth, addressing land fragmentation requires significant funding. Countries like Germany and the Netherlands, offer financial aid and loans for consolidation. Developing countries should establish specialized funds or a "land bank" to centralize acquired land rights, aiding urban migrants' voluntary land transfer. This approach would alleviate financial strain, making land consolidation more feasible and cost-effective.

2.5 Uncertainties and limitations

The uncertainty of changes in the environmental impact of farm size optimization arises mainly from the variations in N emissions, GEOS-Chem modeling, as well as the cost-benefit analysis. The uncertainties could come from the GNB-Farm methods of calculating cropland N_r emissions driving the GEOS-Chem model runs. We made the Monte Carlo simulations using the minmum-maximum values of varied inputs. The ranges of emission factors of N were set within ±20% of the average emission factors, and the bottom and upper limit of N budgets have been presented in **Figs. S22** and **S23**. The global average range of $PM_{2.5}$ mass is around 5% of the annual average value, with cropland NH_3 emission having a 16% varations. The range of premature deaths attributable to $PM_{2.5}$ pollution from the GBD database were from 3.6 to 4.1 million (the median value was 3.9 million premature deaths) on a global scale; the reduction in premature deaths caused by increasing farm size was estimated at 135165-149389 globally with a median value of 142,276. The cost of land consolidation for large-scale farming is related to terrain and local economic conditions, which were also set within ±20% of the average cost of categories (3000-3800 USD ha^{-1}). Damage cost of N emission ($/kg N) were given with Min-Median-Max (**Table S9**), for all numbers given in the main text we show the range of the cost-benefit values (min-max) (**Fig. S21**). All these uncertainies are systematic rather than random, should not affect the spatial patters, temporal changes and conclusions of regional comparisions in this study.

Our study have several limitations. First, the cost-benefit analysis did not include the quantification of the impact of changing farm size on biodiversity, attributed to the limitations of available assessment tools and data. The influence of altering field size on biodiversity can result in both positive and negative outcomes. Larger fields may promote more efficient agricultural practices, potentially reducing the overall impact on natural habitats[17]. However, negative consequences, such as habitat loss and monoculture practices can adversely affect biodiversity[18]. The complexity arises from the interplay of various factors, including agricultural management practices, landscape configuration, and regional ecological context. Accurate quantification necessitates comprehensive, context-specific assessments that account for species diversity, ecosystem functions, and broader ecological dynamics. Second, surface ozone concentrations can be decreased by reducing NO_x emissions, like in the North China Plain, where soil NO_x emissions enhance ozone by up to 8 ppb [19], which was not considered in this analysis due to the lack of global data. Third, the utilization of regional data (EU and USA) with adjustments by social-economic drivers (population and GDP) to estimate costs and benefits for other countries comes with inherent limitations. The constraint lies in the potential variation of agricultural practices, economic structures, and societal dynamics across different countries, which may not be fully captured by the adjustments. We have conducted an uncertainty analysis for our simulations. We recognize the importance of future research efforts to collect more comprehensive and diverse datasets to improve the accuracy and applicability of optimization models across a broader range of countries and contexts.

Figures S1-S20

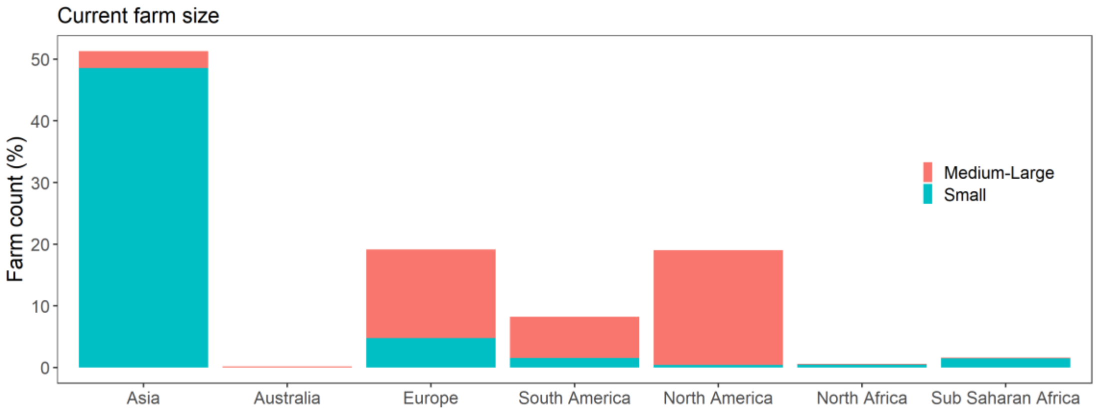

Fig. S1 Percentages of small and medium-large farms by continent. The small and medium-large farms refer to fields with an area of <2.5 ha and >2.5 ha.

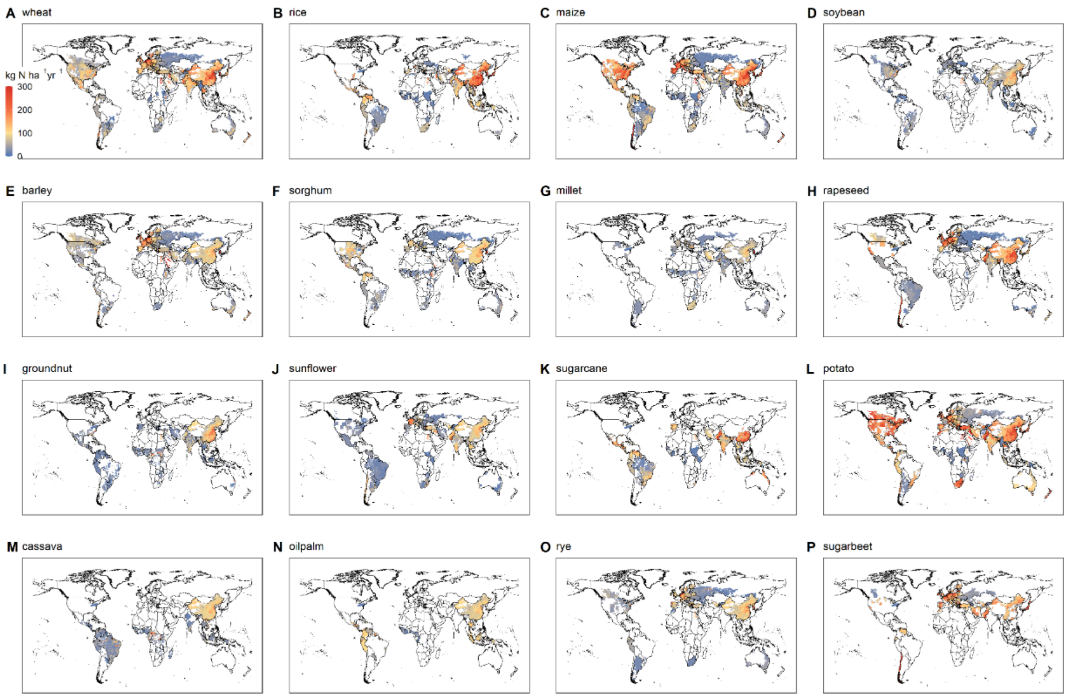

Fig. S2 Spatial distribution of N fertilizer use for 16 major crops in 2020.

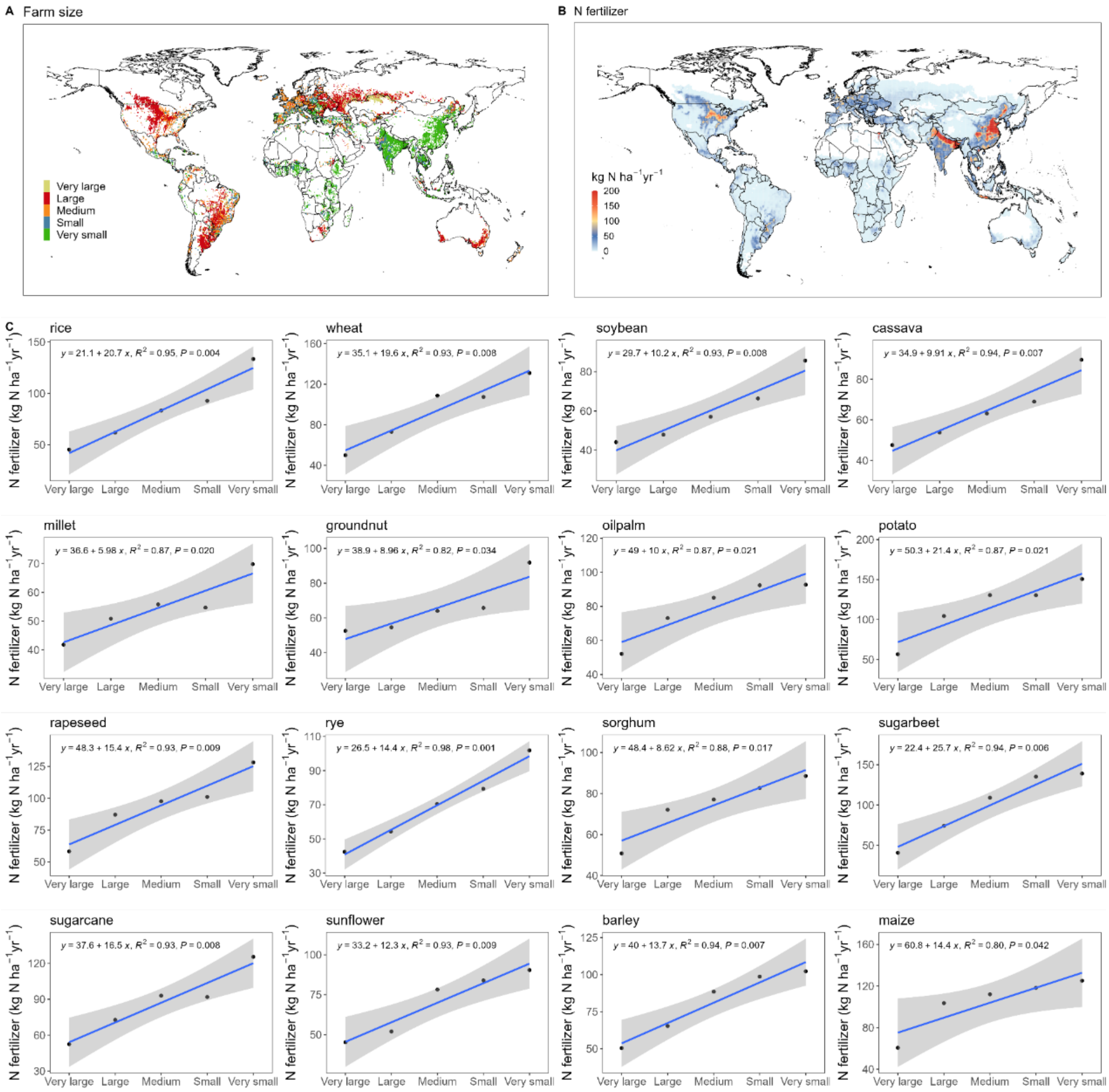

Fig. S3 N fertilizer use and farm size. A, the spatial distribution of farm size based on satellite-derived estimates using Google Maps and Bing and the Geo-Wiki application. The categories are very large (>100 ha), large (16-100 ha), medium (2-16 ha), small (0.5-2 ha), and very small (<0.5 ha); B, the spatial distribution of N fertilizer use on major crops. The spatial maps of N fertilizer use for each crop can be found in Extended Data Fig. 2; C, the correlation of N fertilizer use with farm size for the crops.

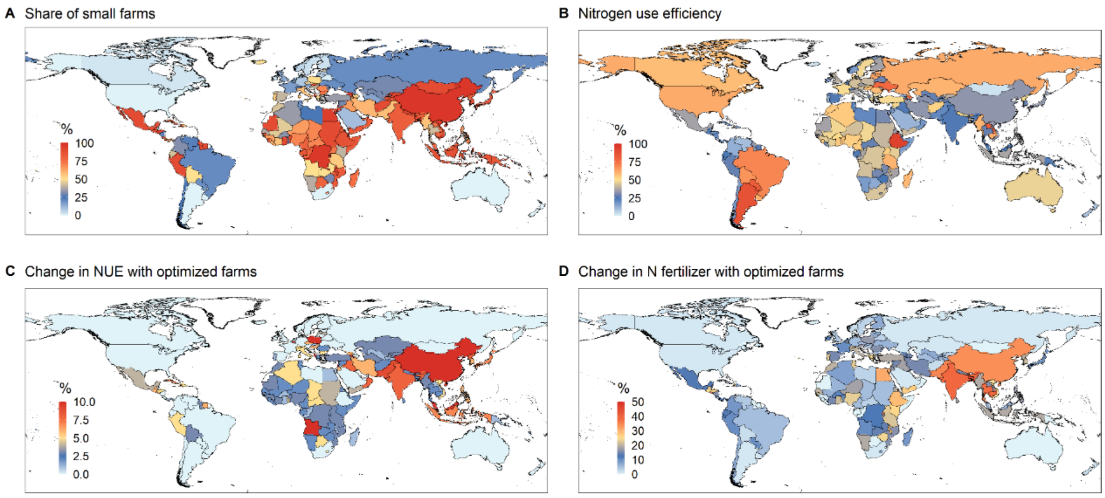

Fig. S4 Effect of optimizing farms in 2020. A, share of small farms (%); B, NUE (%) in 2020; C, change in NUE by optimizing farms under Tier 3; D, change in N fertilizer.

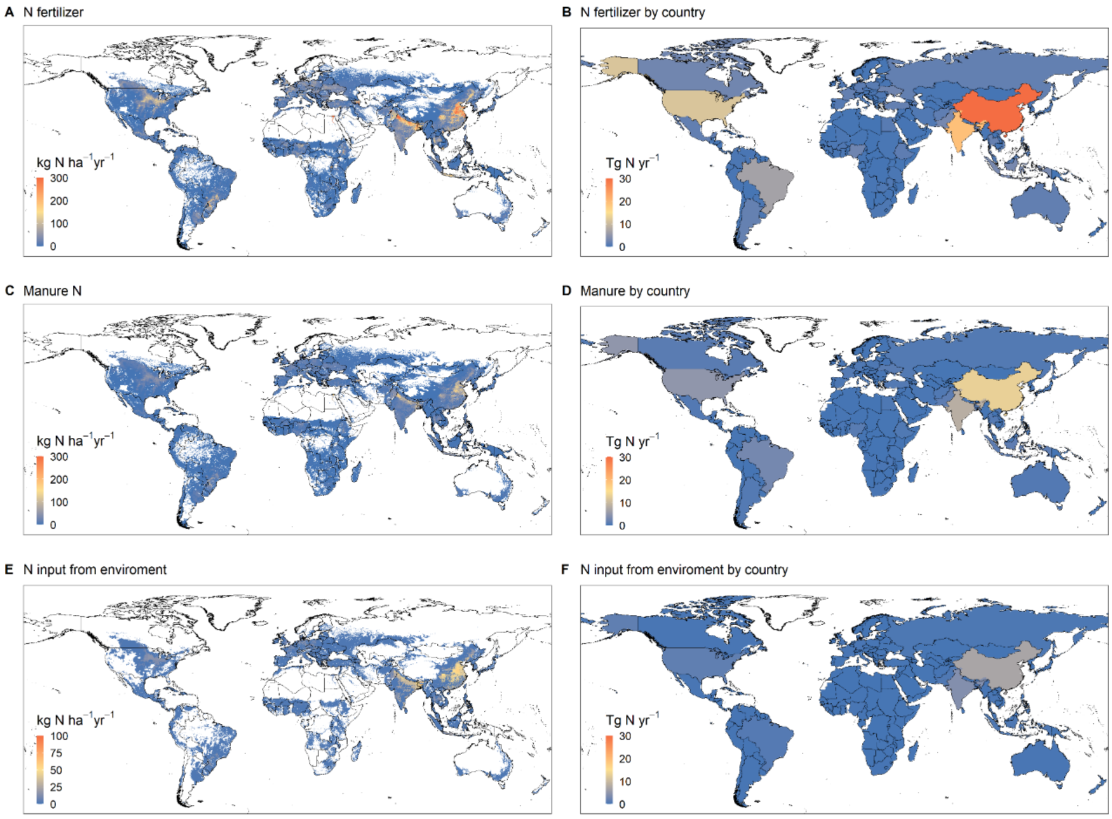

Fig. S5 N inputs to croplands including N fertilizer, manure and environmental N (N fixation, irrigation and deposition) in 2020. A, C and E show gridded values of each N input, while B, D, and F represent country-level total sums of each N input.

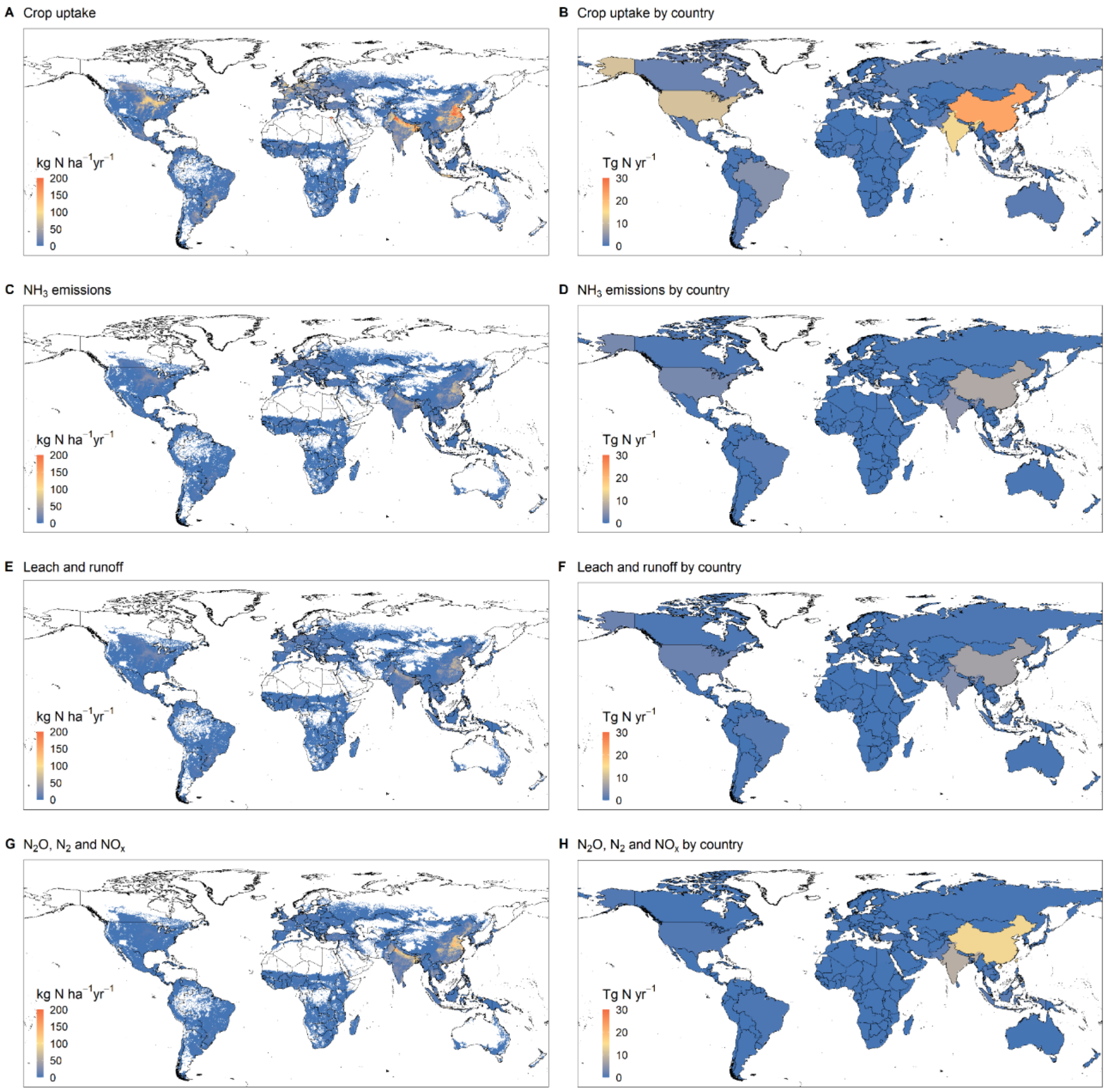

Fig. S6 Cropland N outputs including crop uptake, NH_3 emissions, leach and runoff, and denitrification-nitrification processes (N_2O, N_2 and NO) in 2020. A, C, E and G show gridded values of each N output, while B, D, F, and H show country-level total sums of each N output.

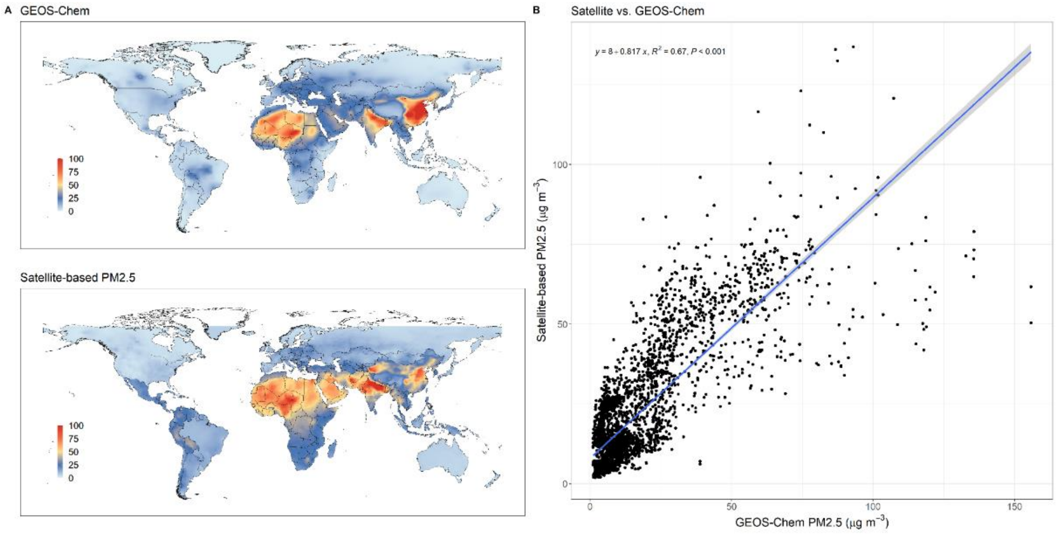

Fig. S7. Comparison of the GEOS-Chem $PM_{2.5}$ exposure estimates with the satellite-derived surface $PM_{2.5}$ exposure estimates for the year 2020.

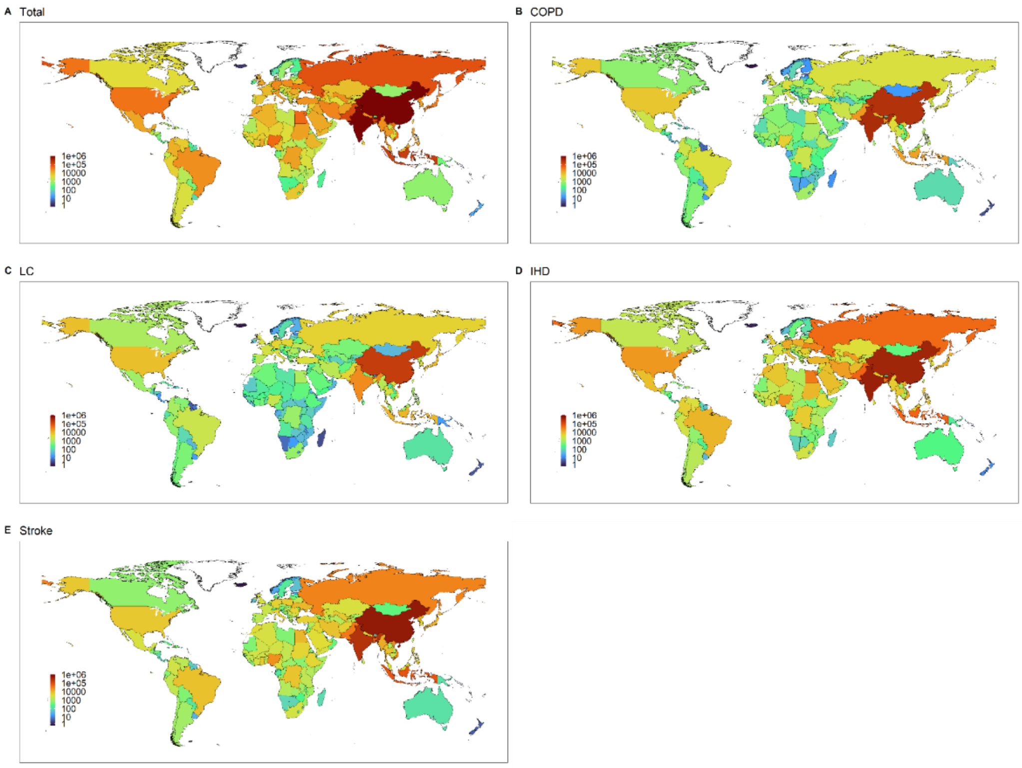

Fig. S8 $PM_{2.5}$ related premature deaths in the year 2020. A, total premature deaths caused by $PM_{2.5}$; B-E, premature deaths of COPD, LC, IHD, and Stroke, respectively.

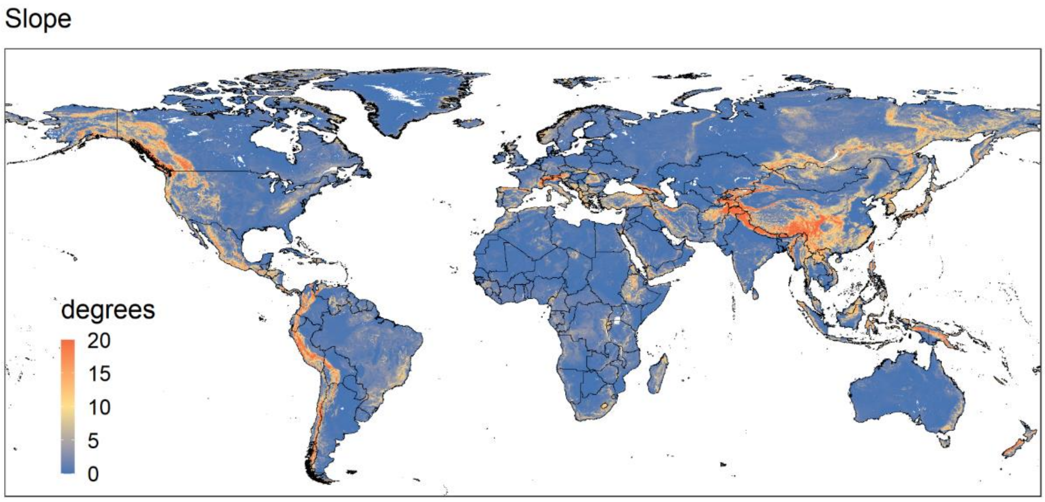

Fig. S9 Calculated terrain slope based on the digital elevation model products of global GMTED2010.

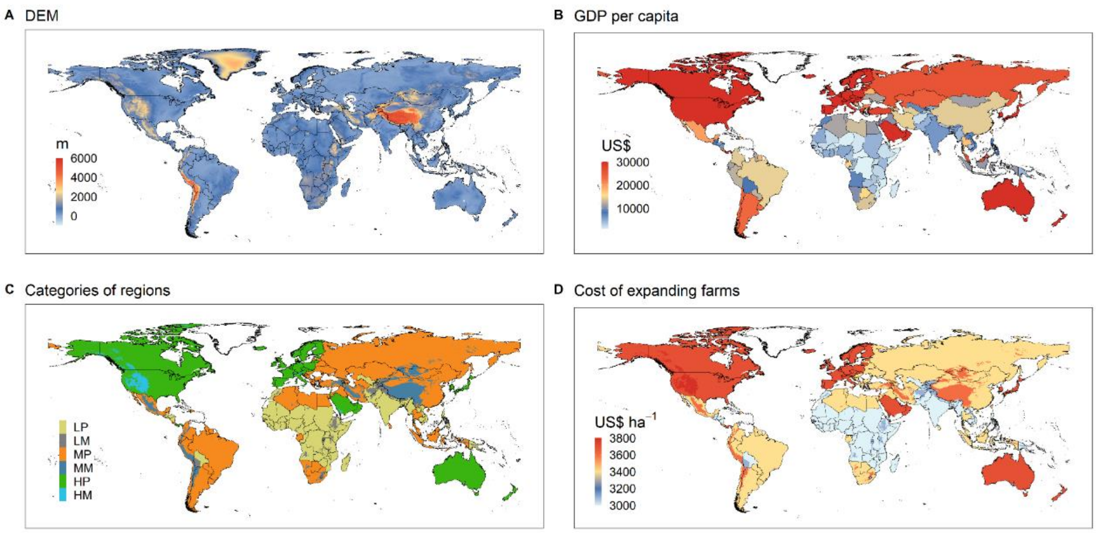

Fig. S10 Data used to estimate the cost of increasing farm size. A, the elevation data from GMTED2010 at 0.0625° grids; B, GDP per capita in 2020; C, six categories used to estimate the implementation costs of increasing farm size: Low-income Plain (LP) and Low-income Mountain plain (LM), Medium-income Plain (MP), Medium-income Mountain plain (MM), High-income Plain (HP), and High-income Mountain plain (HM); D, cost of increasing farm size per ha.

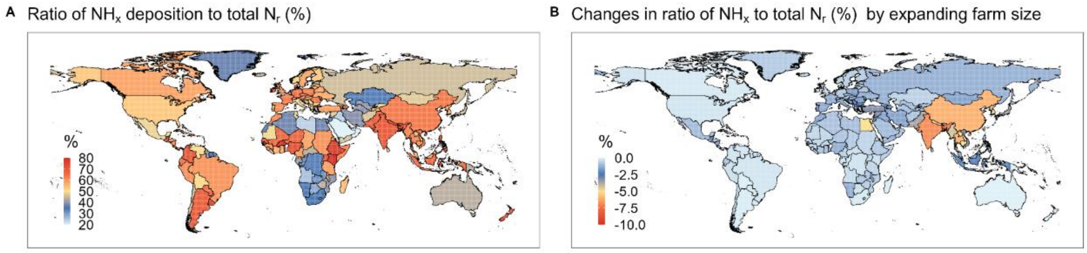

Fig. S11 Impact of increasing farm size on NH_x deposition. A and B show the ratio of NH_x to total N_r deposition and the changes in the ratio of NH_x to total N_r deposition by expanding farm scales in 2020, respectively.

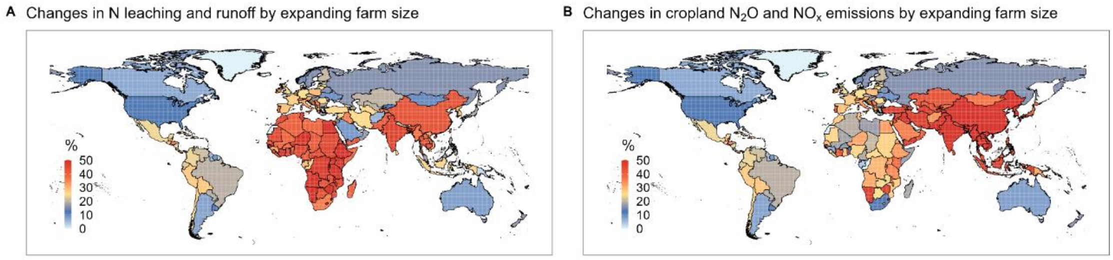

Fig. S12 Impact of increasing farm size on N leaching and runoff (A), and cropland N_2O and NO_x emissions (B).

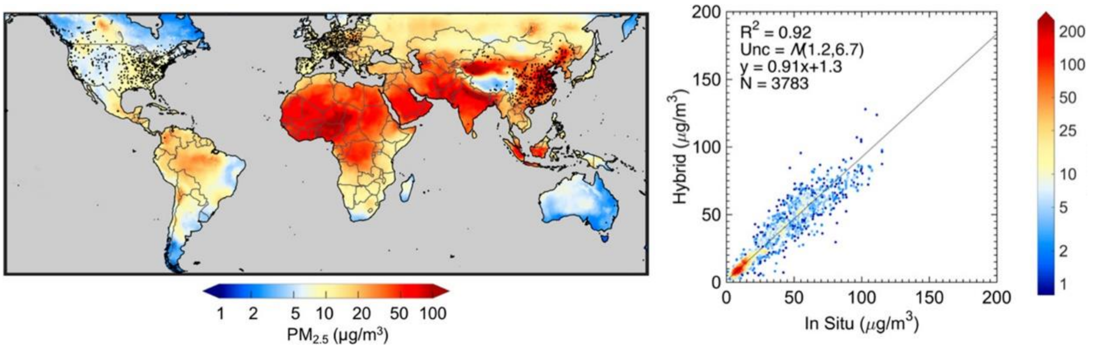

Fig. S13. Comparision of satellite-derived $PM_{2.5}$ concentrations with ground-based measurements [20]. Left: Black dots represent monitor locations. Right: Annual mean $PM_{2.5}$ versus annual mean *in situ* values. The color-scale indicates the number density of observations at each point.

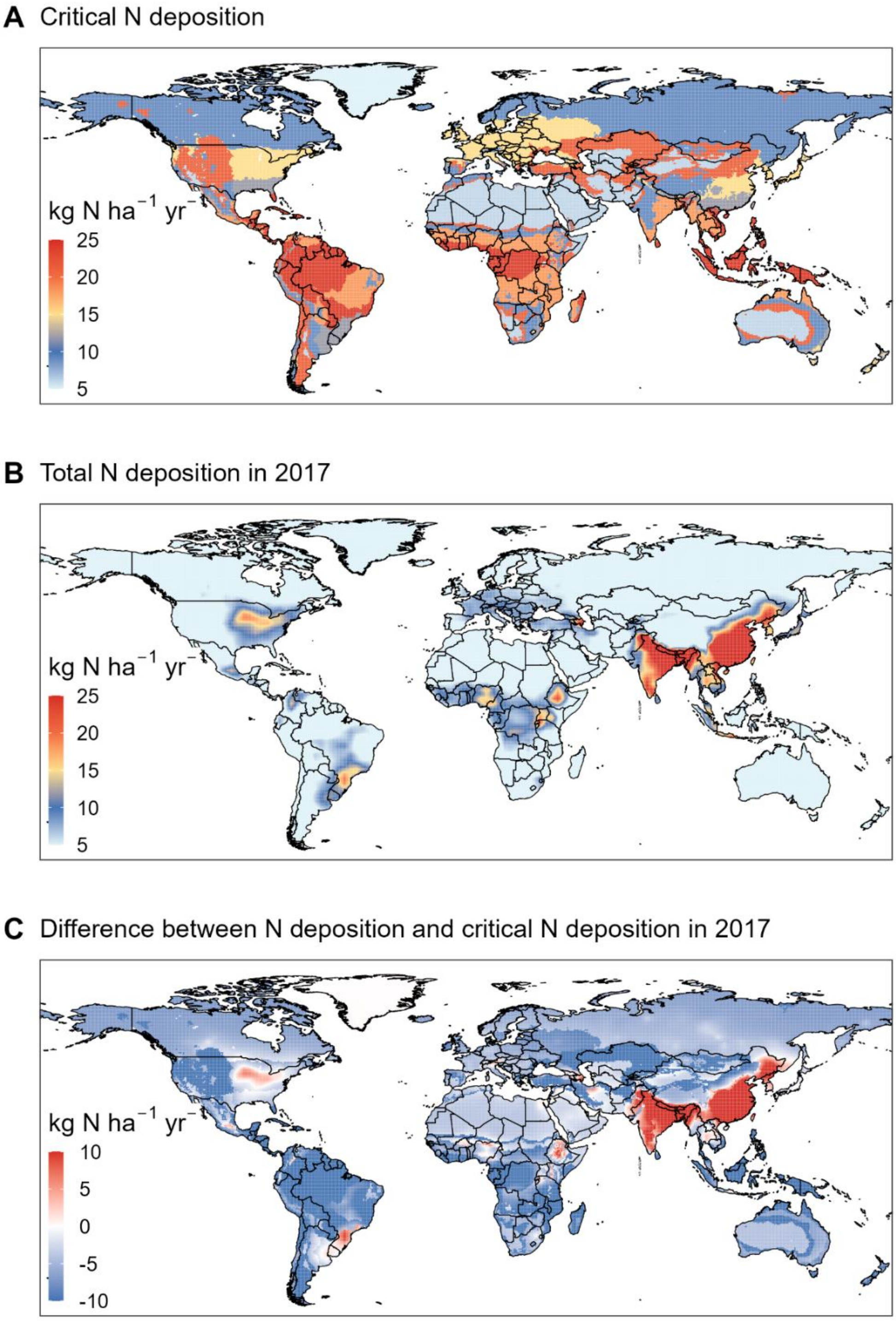

Fig. S14 Comparison of current N deposition with the critical N deposition. A, The spatial variation in critical N deposition (kg N ha^{-1} yr^{-1}) based on Schulte-Uebbing et al. [6]; B, Total N deposition as estimated from this study; C, the differences between current N deposition and critical N deposition.

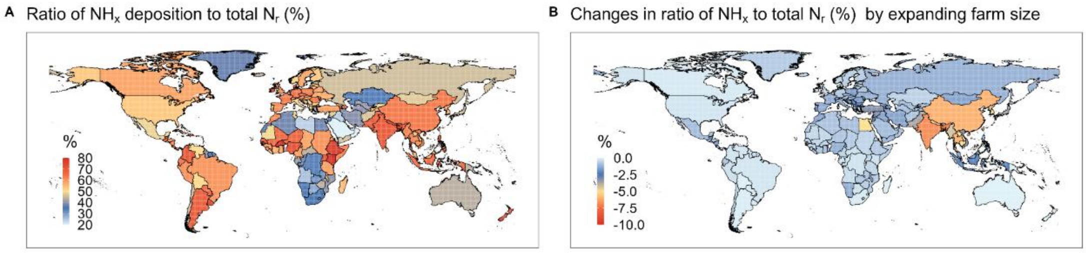

Fig. S15 Impact of increasing farm size on NH_x deposition. A and B show the ratio of NH_x to total N_r deposition and the changes in the ratio of NH_x to total N_r deposition by expanding farm scales, respectively.

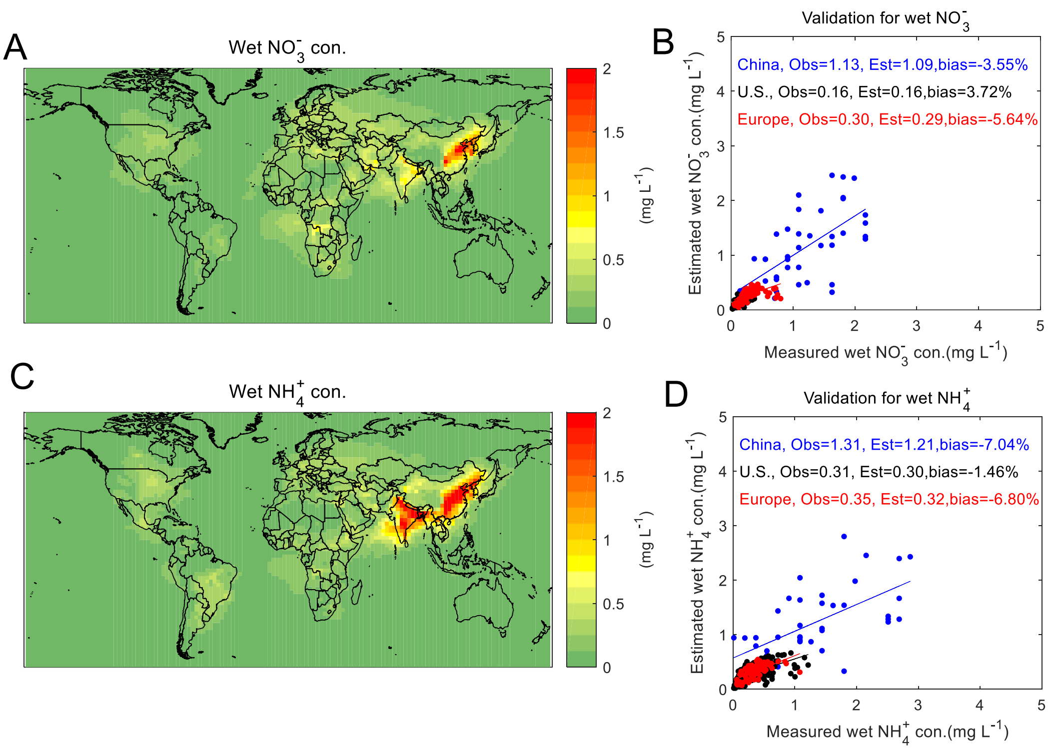

Fig. S16 Assessment of GEOS-Chem modeled NH_x and NO_y. A and C showcase spatial maps of wet NH_4^+ and NO_3^- concentrations, respectively, while B and D present a comparison between modeled wet NH_4^+ and NO_3^- concentrations with ground-based measurements conducted by NNDMN in China, EMEP in Europe, and NADP in the USA.

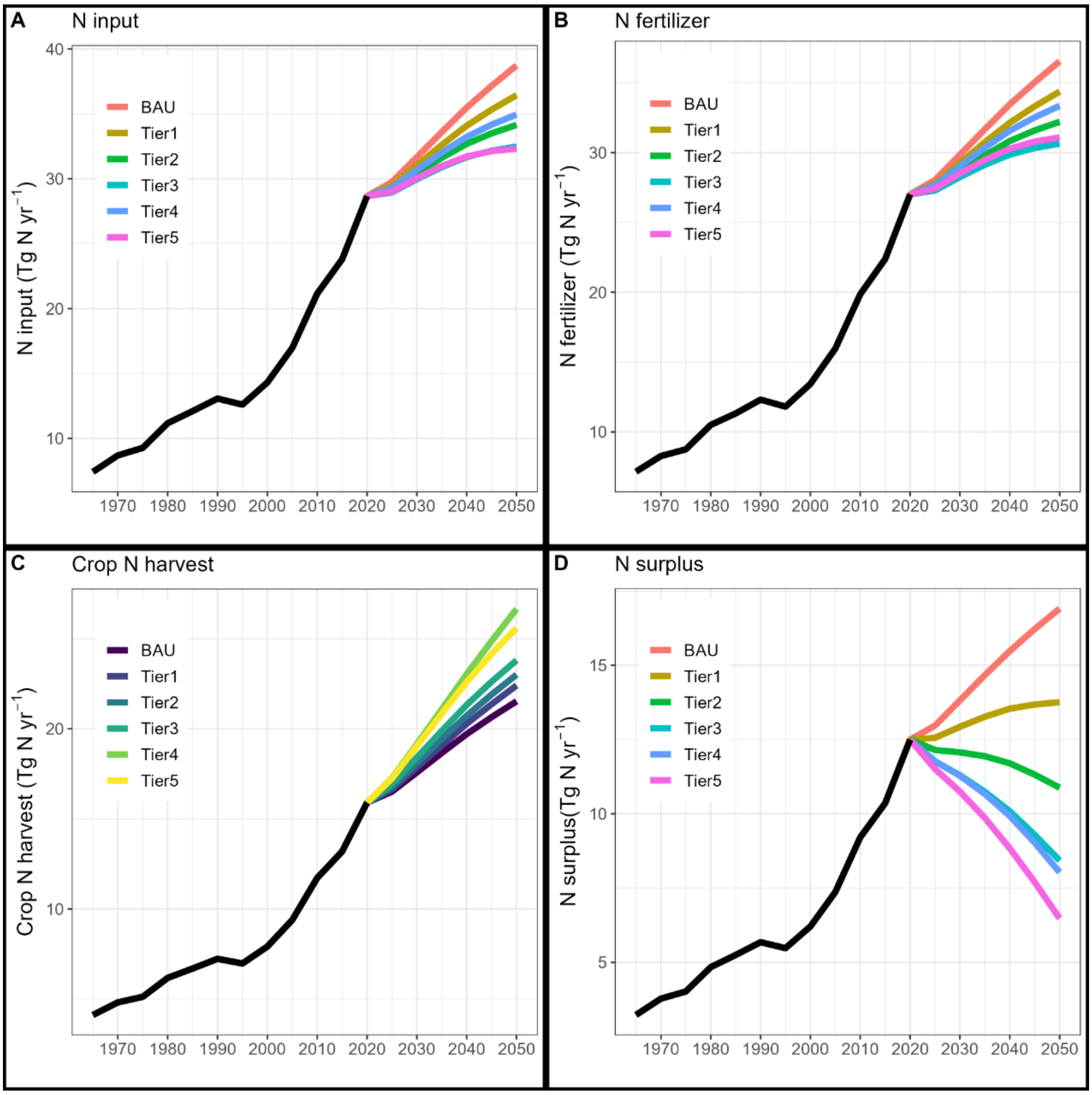

Fig. S17 Future trends under the BAU and tiered approaches towards 2050 in Africa. A, long-term (1965-2050) changes in cropland N input (including synthetic fertilizer, manure and the environment). B, fertilizer N use (synthetic fertilizer plus manure). C, crop N harvest, D, N surplus (the difference between total N input and crop N uptake).

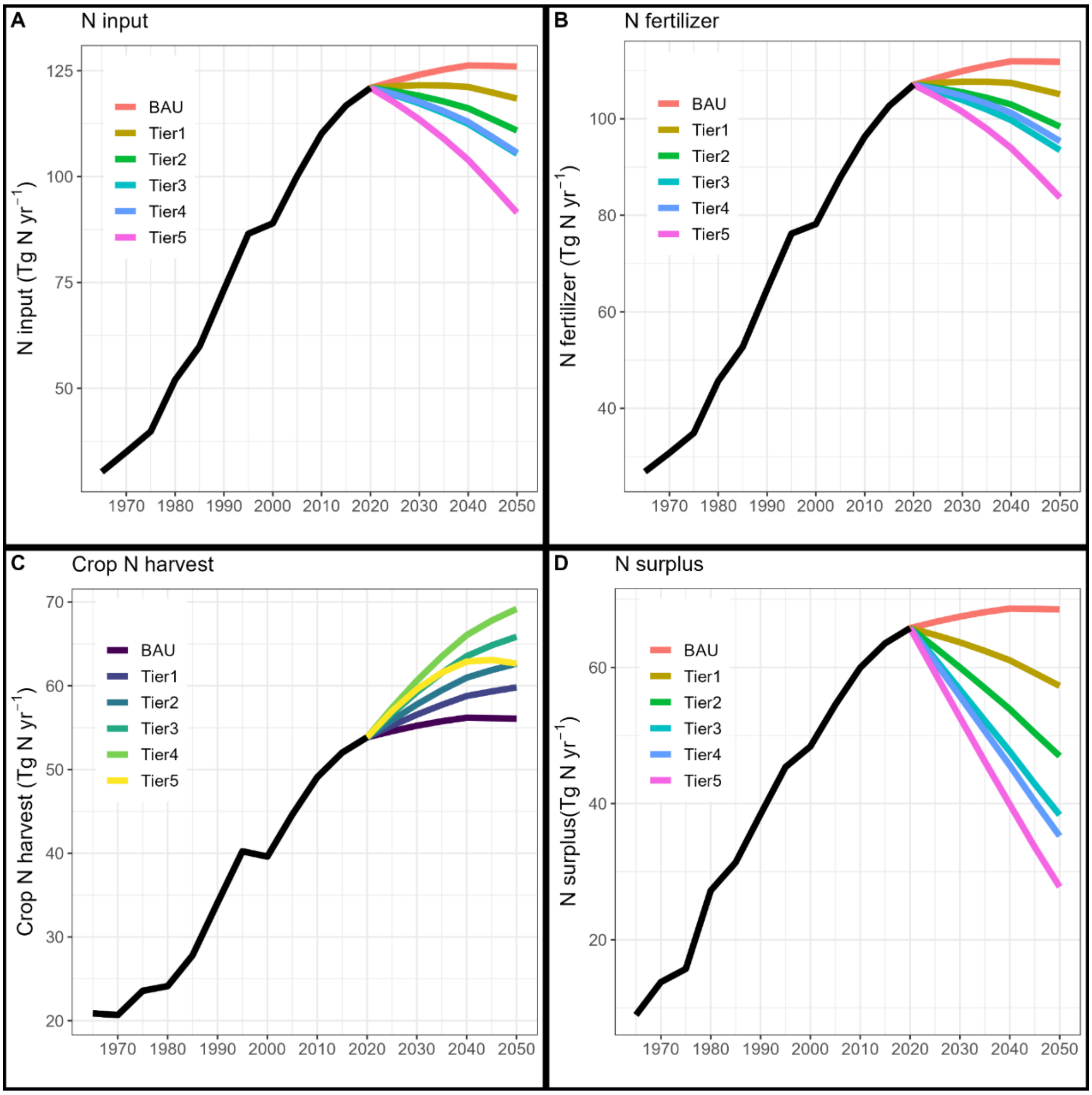

Fig. S18 The same as Fig. S17 but for Asia.

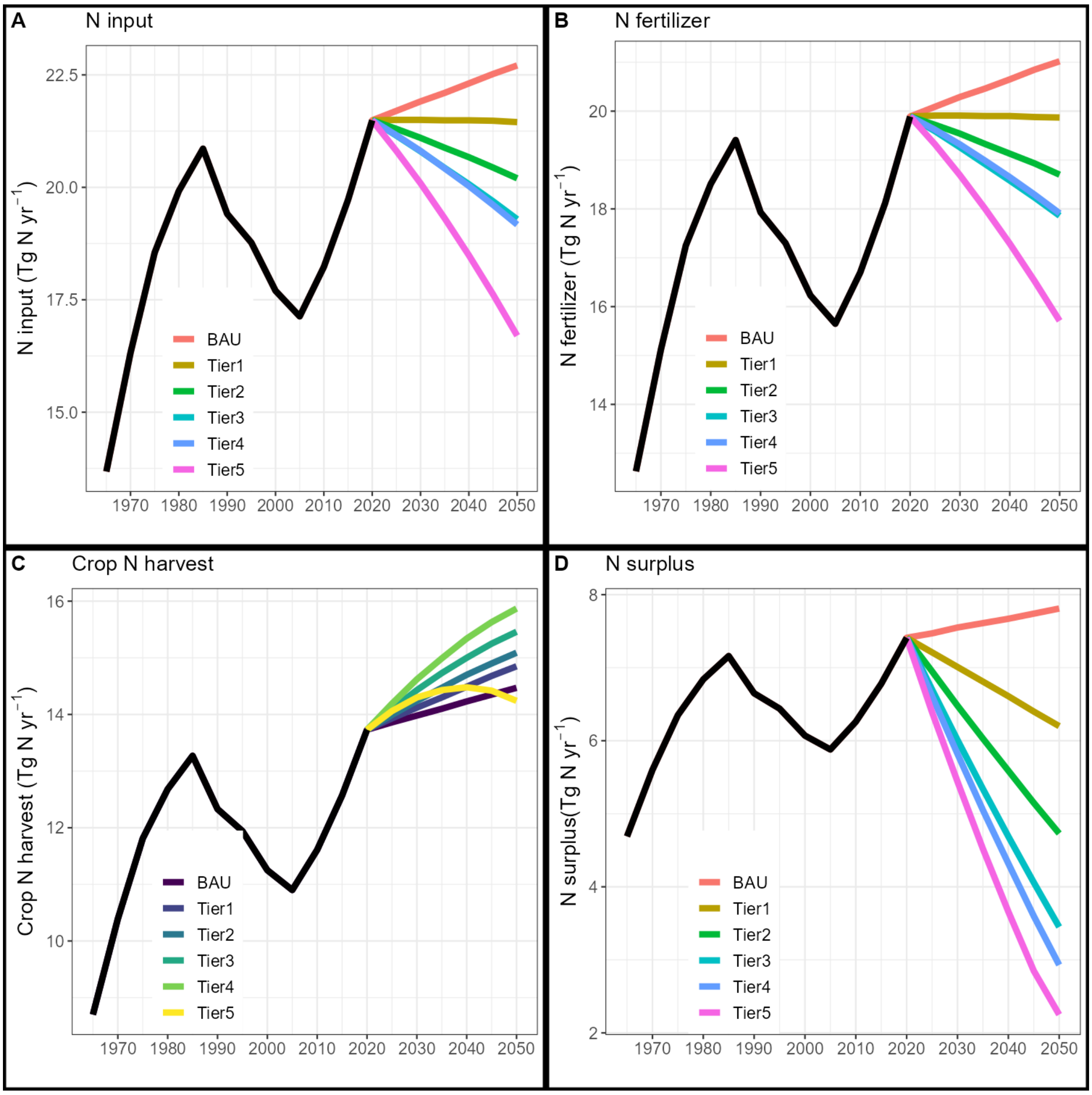

Fig. S19 The same as Fig. S17 but for Europe

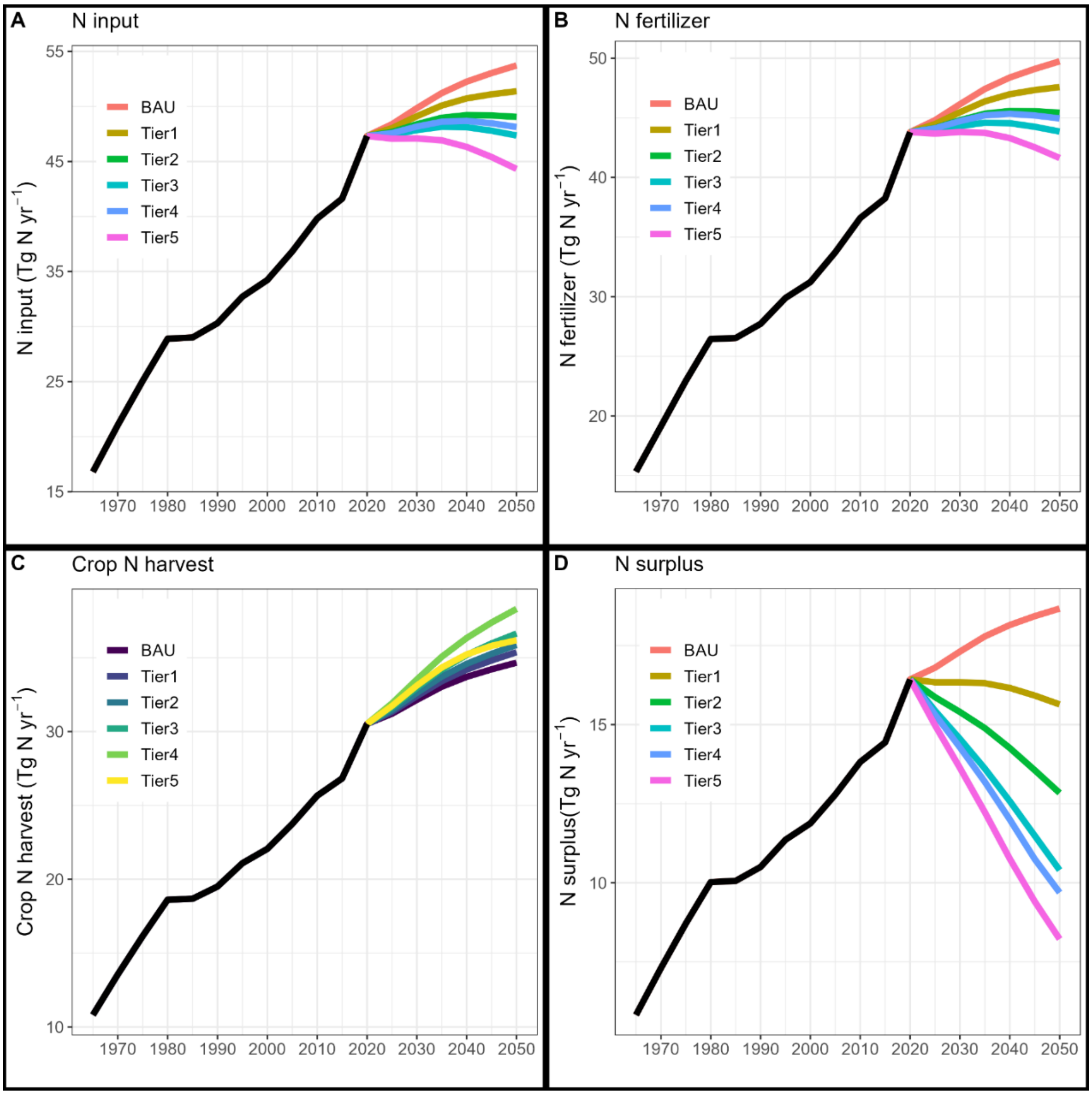

Fig. S20 The same as Fig. S17 but for Americas

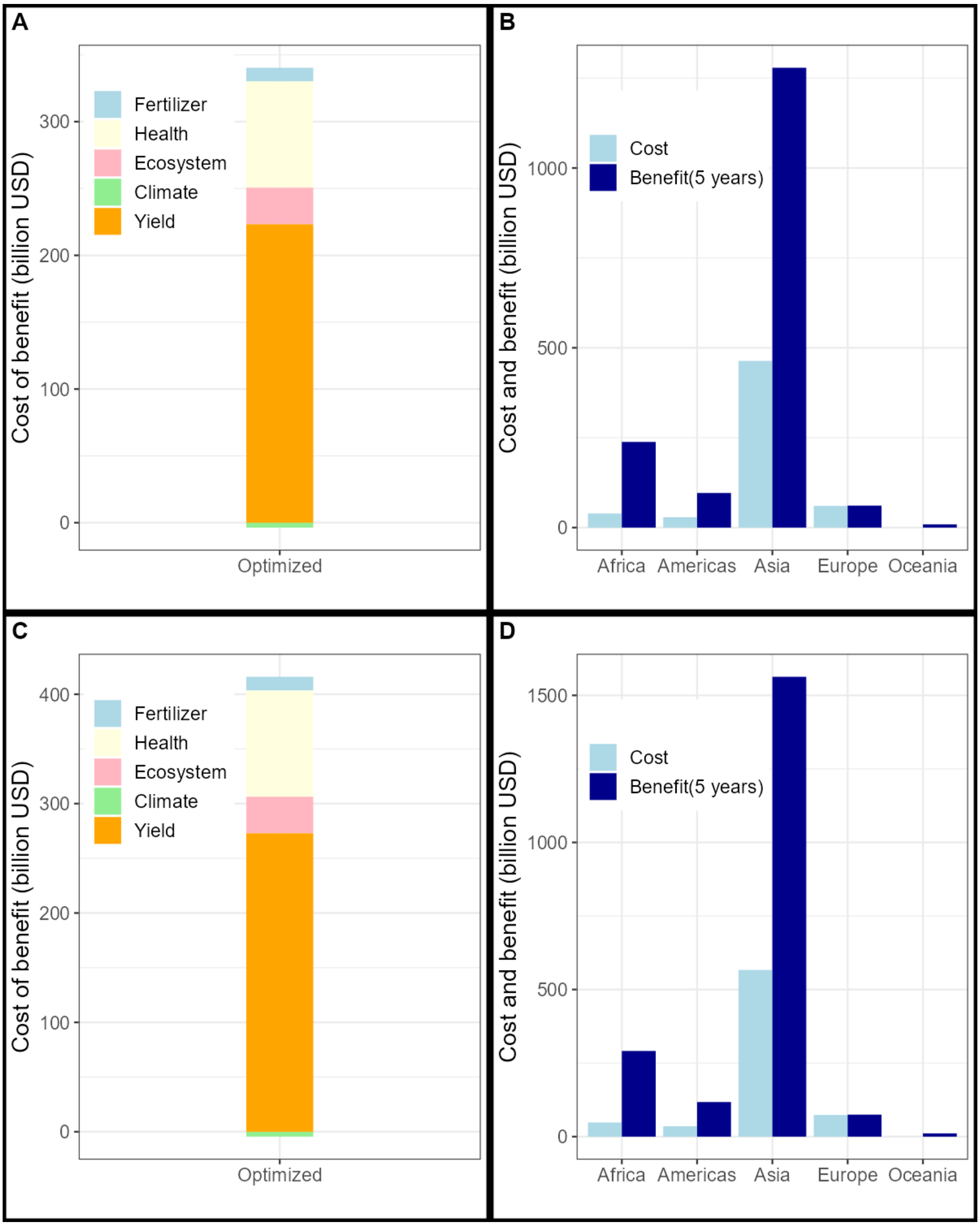

Fig. S21 The bottom (A and B) and upper (C and D) limit of cost and benefit in 2020 based on scenario analysis.

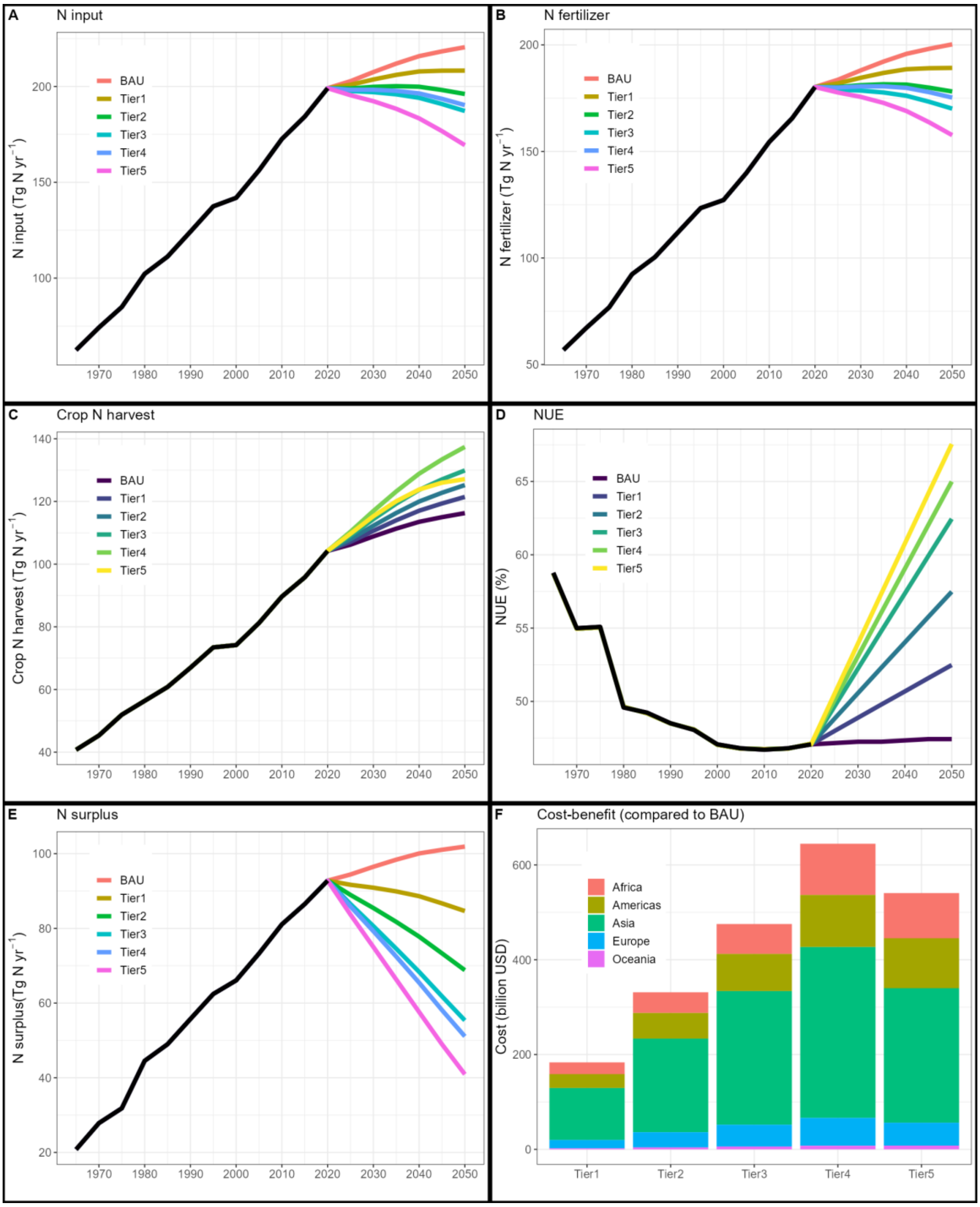

Fig. S22 The bottom limit of future trends under the BAU and tiered approaches towards 2050. A, long-term (1965-2050) changes in cropland N input (including synthetic fertilizer, manure and the environment). B, fertilizer N use (synthetic fertilizer plus manure). C, crop N harvest, D, cropland NUE. E, N surplus (the difference between total N input and crop N uptake). F, cost-benefit analysis compared to the BAU in 2050 including fertilizer saving, human health, ecosystem, climate and yields.

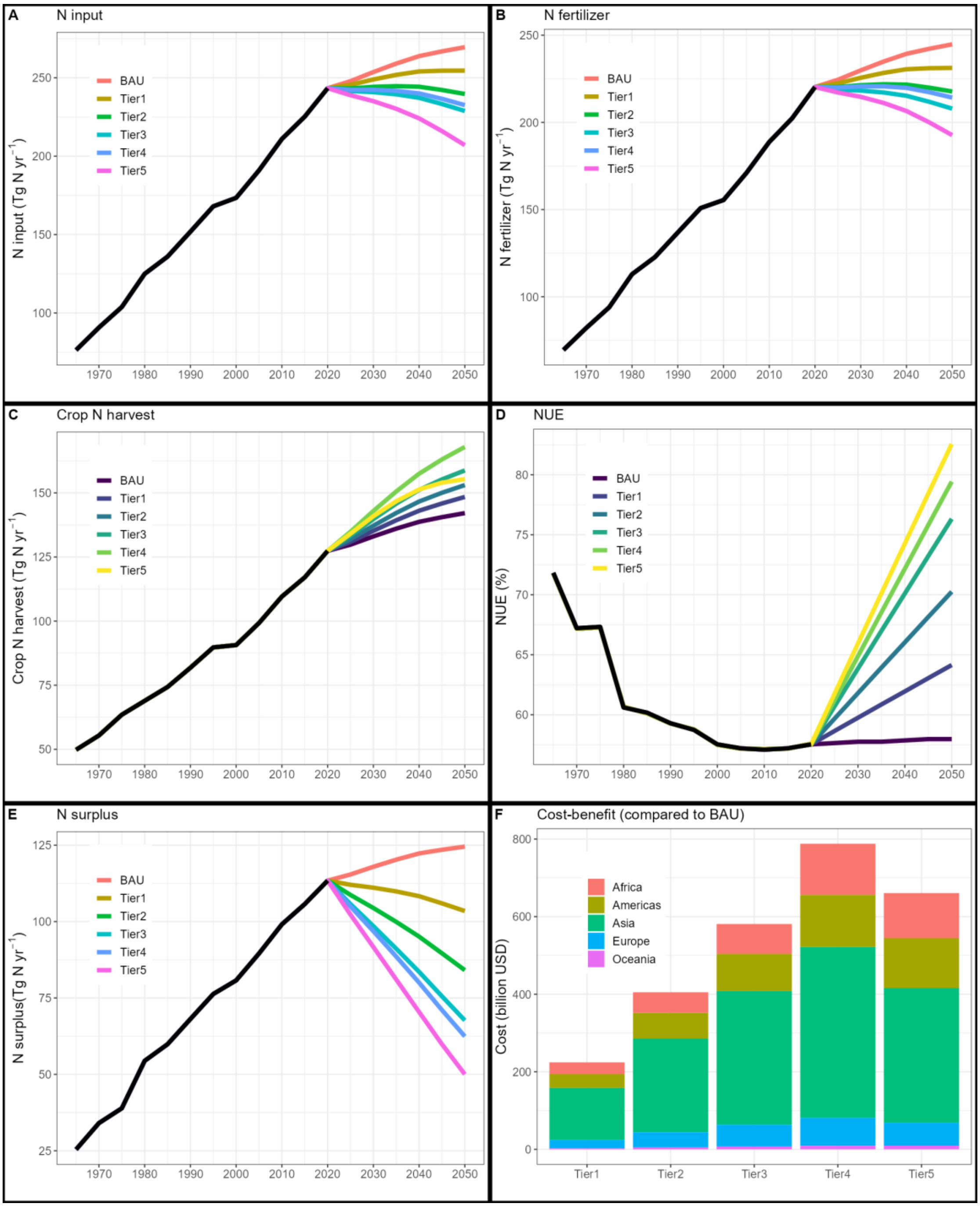

Fig. S23 The upper limit of future trends under the BAU and tiered approaches towards 2050. A, long-term (1965-2050) changes in cropland N input (including synthetic fertilizer, manure and the environment). B, fertilizer N use (synthetic fertilizer plus manure). C, crop N harvest, D, cropland NUE. E, N surplus (the difference between total N input and crop N uptake). F, cost-benefit analysis compared to the BAU in 2050 including fertilizer saving, human health, ecosystem, climate and yields.

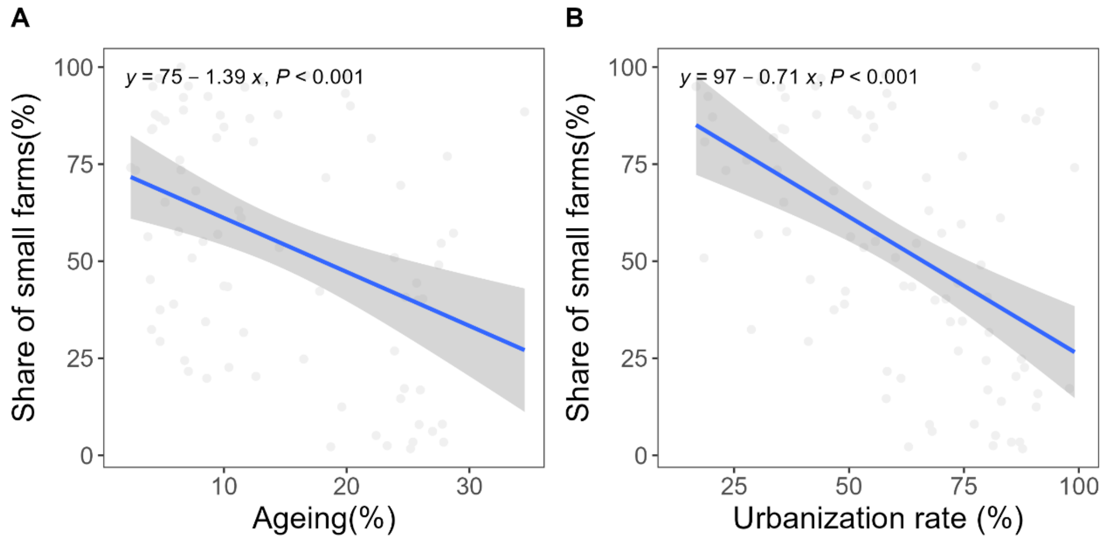

Fig. S24 Relationship of the share of small farms with ageing (A) and urbanization (B).

Tables S1-S8

Table S1 N fertilizer use and production data for major crops in 2010.

Crop	**N fer (kg ha^{-1})**	**N fet (10^9 kg)**	**Share (%)**	**Harvest area (10^6 ha)**	**Share of area (%)**	**Yield (ton ha^{-1})**
barley	75.3	3.9	4.8	53	6.44	2.36
cassava	63.6	0.5	0.6	15	1.81	10.95
maize	104.7	17.2	21.3	22	2.63	1.47
millet	53.9	1.1	1.4	134	16.13	3.34
groundnut	60.1	1.4	1.8	33	3.98	1.1
oil palm	90.0	0.7	0.8	9	1.13	13.36
potato	132.8	2.4	2.9	19	2.29	16.02
rapeseed	103.1	3.2	4.0	24	2.89	1.33
rice	102.6	19.2	23.6	147	17.71	3.15
rye	67.5	0.6	0.7	9	1.12	1.87
sorghum	72.9	1.8	2.3	38	4.64	2.09
soybean	62.2	4.0	4.9	73	8.87	1.59
sugar beet	125.7	0.8	1.0	6	0.73	30.1
sugarcane	103.9	2.4	2.9	19	2.32	59.14
sunflower	60.0	1.0	1.3	20	2.44	1.13
wheat	97.9	21.0	25.9	206	24.88	2.43

Table S2. The implantation efficiency of optimizing farms for different tiers and the BAU for the years 2020-2050.

	2020	2030	2040	2050
BAU	Eff. = 0%	Eff. = 0%	Eff. = 0%	Eff. = 0%
Tier 1	Share: >50%, Eff= 0.20	Share: >50%, Eff= 0.40	Share: >50%, Eff= 0.60	Share: >50%, Eff= 0.80
	Share:30-50%, Eff= 0.18	Share:30-50%, Eff= 0.38	Share:30-50%, Eff= 0.58	Share:30-50%, Eff= 0.78
	Share: <30%, Eff= 0.16	Share: <30%, Eff= 0.36	Share: <30%, Eff= 0.56	Share: <30%, Eff= 0.76
Tier 2	Share: >50%, Eff= 0.24	Share: >50%, Eff= 0.44	Share: >50%, Eff= 0.64	Share: >50%, Eff= 0.84
	Share:30-50%, Eff= 0.22	Share:30-50%, Eff= 0.42	Share:30-50%, Eff= 0.62	Share:30-50%, Eff= 0.82
	Share: <30%, Eff= 0.20	Share: <30%, Eff= 0.40	Share: <30%, Eff= 0.60	Share: <30%, Eff= 0.80
Tier 3	Share: >50%, Eff= 0.28	Share: >50%, Eff= 0.48	Share: >50%, Eff= 0.68	Share: >50%, Eff= 0.88
	Share:30-50%, Eff= 0.26	Share:30-50%, Eff= 0.46	Share:30-50%, Eff= 0.66	Share:30-50%, Eff= 0.86
	Share: <30%, Eff= 0.24	Share: <30%, Eff= 0.44	Share: <30%, Eff= 0.64	Share: <30%, Eff= 0.84
Tier 4	Share: >50%, Eff= 0.32	Share: >50%, Eff= 0.52	Share: >50%, Eff= 0.72	Share: >50%, Eff= 0.92
	Share:30-50%, Eff= 0.30	Share:30-50%, Eff= 0.50	Share:30-50%, Eff= 0.70	Share:30-50%, Eff= 0.90
	Share: <30%, Eff= 0.28	Share: <30%, Eff= 0.48	Share: <30%, Eff= 0.68	Share: <30%, Eff= 0.88
Tier 5	Share: >50%, Eff= 0.36	Share: >50%, Eff= 0.56	Share: >50%, Eff= 0.76	Share: >50%, Eff= 0.96
	Share:30-50%, Eff= 0.34	Share:30-50%, Eff= 0.54	Share:30-50%, Eff= 0.74	Share:30-50%, Eff= 0.94
	Share: <30%, Eff= 0.32	Share: <30%, Eff= 0.52	Share: <30%, Eff= 0.72	Share: <30%, Eff= 0.92

The “share” means the percentage of small farms in a country; the efficiency means the implententation efficiency (%) of optimizing farms.

Table S3. Nitrogen budgets in 2020 and those with optimizing farms.

	N dep.	Fertilizer	Manure	Fixation	Irrigation	NH_3	Crop	Leach	Gas*	
Africa	0.058	10.552	16.458	1.125	0.469	4.827	15.901	4.259	3.407	2020
Americas	0.901	27.904	15.902	1.836	0.765	7.393	30.515	6.632	2.407	2020
Asia	10.831	69.626	37.403	2.156	0.898	17.941	53.847	15.552	32.279	2020
Europe	0.274	14.3	5.588	0.934	0.389	2.748	13.727	3.169	1.488	2020
Oceania	0	1.509	1.016	0.208	0.087	0.444	1.801	0.416	0.118	2020
Africa	0.056	9.746	16.458	1.126	0.452	4.625	18.75	1.993	2.206	Optimized
Americas	0.891	27.367	15.902	1.838	0.75	7.309	31.545	5.623	1.912	Optimized
Asia	10.216	60.107	37.403	2.158	0.847	10.951	65.695	9.856	22.977	Optimized
Europe	0.266	13.778	5.588	0.935	0.378	2.676	14.207	2.47	1.242	Optimized
Oceania	0	1.505	1.016	0.208	0.086	0.442	1.884	0.36	0.088	Optimized

*The Gas means the sum of N_2, N_2O and NO_x emissions. The unit is Tg N yr^{-1}.

Table S4. Global nitrogen budgets based on GNF-Farm under the BAU.

Year	N dep.	Fertilizer	Manure	Fixation	Irrigation	NH_3	Crop	Leach	Gas*
1965	3.67	19.15	44.01	2.356	0.206	8.893	45.285	8.267	5.945
1970	4.428	28.73	45.92	3.018	0.379	11.684	50.358	11.248	8.025
1975	5.033	37.084	48.297	3.394	0.548	13.387	57.714	12.864	9.116
1980	6.248	52.178	50.466	3.922	0.767	16.041	62.639	15.445	17.993
1985	6.861	59.193	52.36	4.208	0.96	17.326	67.547	16.783	20.308
1990	8.211	67.872	56.504	4.326	1.12	19.268	74.382	18.657	23.997
1995	9.666	76.651	60.483	4.589	1.323	21.242	81.592	20.564	27.556
2000	9.957	78.733	62.601	4.844	1.533	23.711	82.416	21.257	28.449
2005	11.322	88.898	66.537	5.091	1.747	26.139	90.238	23.399	31.877
2010	12.574	102.256	69.343	5.555	2.048	28.915	99.61	25.888	35.283
2015	12.64	112.46	71.481	5.856	2.303	30.872	106.418	27.672	37.573
2020	12.065	123.891	76.367	6.258	2.607	33.353	115.791	30.029	39.698
2025	12.218	126.04	77.992	6.368	2.653	34.004	117.997	30.584	40.327
2030	12.33	128.704	80.235	6.549	2.729	34.843	120.927	31.321	41.041
2035	12.407	131.21	82.325	6.724	2.802	35.631	123.682	32.01	41.678
2040	12.475	133.339	84.228	6.876	2.865	36.328	126.1	32.617	42.229
2045	12.439	134.623	85.588	6.991	2.913	36.787	127.751	33.018	42.459
2050	12.412	135.66	86.849	7.088	2.953	37.188	129.188	33.367	42.652

*The Gas means the sum of N_2, N_2O and NO_x emissions. The unit is Tg N yr^{-1}.

Table S5 Comparisons of share of small and large field size across regions.

Regions	remote sensing		agricultural census data	
	<2 ha	>2ha	<2 ha	>2ha
Brazil	20.1	79.9	20.3	79.7
Canada	2.9	97.1	2.5	97.5
China	94.1	5.9	97.9	2.1
France	17.3	82.7	16.8	83.2
India	82.3	17.7	81.8	18.2
Indonesia	86.5	13.5	87.6	12.4
Italy	59.1	41.9	57.2	42.8
Laos	71.2	28.8	73.5	26.5
Pakistan	56.3	43.7	57.6	42.4
USA	0.2	99.8	0.3	99.7

Table S6. Fractions of NH_3 emissions and leach and ruoff in 2020 based on the GNB-Farm

Regions	NH_3 emissions	Leach/ runoff	Crop	Gas
Africa	0.168 (0.13-0.2)	0.148 (0.12-0.18)	0.553 (0.44-0.66)	0.118 (0.09-0.14)
Americas	0.159 (0.13-0.19)	0.138 (0.11-0.17)	0.645 (0.52-0.77)	0.049 (0.04-0.06)
Asia	0.148 (0.12-0.18)	0.128 (0.1-0.15)	0.445 (0.36-0.53)	0.267 (0.21-0.32)
Europe	0.127 (0.1-0.15)	0.147 (0.12-0.18)	0.638 (0.51-0.77)	0.069 (0.06-0.08)
Oceania	0.158 (0.13-0.19)	0.148 (0.12-0.18)	0.64 (0.51-0.77)	0.041 (0.03-0.05)

Table S7 Comparison of agricultural NH_3 emissions from cropping with previous studies.

Data source	Other estimates	This study	Year
	Global		
EDGAR	31.8	28.9	2010
CEDS	36.2	28.9	2010
Zhao et al. [21]	43	27.5	2006-2010
Olivier et al. [22]	30.6	19.3	1990
Galloway, et al. [23]	19.8	20.2	1993
Fowler et al. [24]	30	28.9	2010
	European Union (EU, 28)		
EDGAR	2.1	2.3	2010
CEDS	2.7	2.3	2010
EMEP	2.9	2.3	2010
Paulot et al. [24]	2.6	2.2	2005-2008
Zhang et al. [25]	3.4	2.3	2000-2010
European Environment Agency (2018) [26]	3.2	2.3	2010
	China		
EDGAR	6.8	7.4	2010
CEDS	7.8	7.4	2010
REAS	8.9	7.4	2010
Streets et al.[27]	4.9	6.3	2000
Wang et al.[28]	5.4	7.2	2005
Zhang et al. [29]	6.4	7.4	2008
Zhang, et al. [30]	6.2	7.1	2000-2010
Dong et al.[31]	5.4	7.2	2005
	United States (US)		
EDGAR	2.8	2.9	2010
CEDS	2.7	2.9	2010
Zhang, et al. [30]	3.0	2.9	2000-2010
Cao et al.[32]	3.9	3.0	2014
NEI	3.1	3.1	2006

Table S8. Damage cost of N emission ($/kg N)

	Effect	Type	Subject	Low	Median	High
NO_x	Increased incidence of respiratory disease	human health	air/climate	12.88	23.1	38.63
	Declining visibility—loss of aesthetics	human health	air/climate	0.31	0.31	0.31
	Increased effects of airborne particulates/increased carbon sequestration in forests (includes benefits)	climate	air/climate	-11.59	-4.51	2.58
	Increased damages to buildings from acid	ecosystem	land	0.09	0.09	0.09
	Increased ozone exposure to crops	ecosystem	land	1.29	1.51	2.58
	Increased ozone exposure to forests	ecosystem	land	0.89	0.89	0.89
	Increased loss of plant biodiversity from N enrichment	ecosystem	land	2.58	7.73	12.88
NH_3	Increased incidence of respiratory disease	human health	air/climate	2.58	4.93	25.75
	Declining visibility—loss of aesthetics	human health	air/climate	0.31	0.31	0.31
	Increased effects of airborne particulates/increased carbon sequestration in forests (includes benefits)	human health	air/climate	-3.86	-1.93	-1.93
	Increased damages to buildings from particulates	ecosystem	land	0.09	0.09	0.09
	Increased loss of plant biodiversity	ecosystem	land	2.58	7.73	12.88
N_2O	Increased ultra-violet light exposure from ozone—humans	human health	air/climate	1.29	1.33	3.86
	Increased emission of a greenhouse gas	climate	air/climate	5.2	13.5	21.9
	Increased ultra-violet light exposure from ozone-crops	ecosystem	air/climate	1.33	1.33	1.33
N runoff	Declining waterfront property value	ecosystem	freshwater	0.21	0.21	0.21
	Loss of recreational use	ecosystem	freshwater	0.17	0.17	0.17
	Loss of endangered species	ecosystem	freshwater	0.01	0.01	0.01
	Increased eutrophication	ecosystem	freshwater	6.44	16.1	25.75
	Undesirable odor and taste	human health	drinking water	0.14	0.14	0.14
	Nitrate contamination	human health	drinking water	0.54	0.54	0.54
	Increased colon cancer risk	human health	drinking water	1.76	1.76	5.15
N leaching	Undesirable odor and taste	human health	drinking water	0.14	0.14	0.14
	Nitrate contamination	human health	drinking water	0.54	0.54	0.54
	Increased colon cancer risk	human health	drinking water	1.76	1.76	5.15
coastal N loading	Loss of recreational use	ecosystem	coastal zone	6.38	6.38	6.38
	Declines in fisheries and estuarine/marine habitat	ecosystem	coastal zone	6	15.84	26

The figures presented in this table represent the original values specific to the EU and US. Negative values indicate an economic benefit based on Gu et al. [33].

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