Farming the planet with better nitrogen use

Pu Liu
Lanzhou University
Hang Xu
Lanzhou University
Sheng Liu
Lanzhou University
Jia Ding
Lanzhou University
Xiankai Lu
South China Botanical Garden, Chinese Academy of Sciences https://orcid.org/0000-0001-7720-6048
Buqing Zhong
Chinese Academy of Sciences https://orcid.org/0000-0001-5706-3107
Yixin Guo
Peking University and IIASA https://orcid.org/0000-0003-4958-7044
Xiao Lu
Sun Yat-sen University https://orcid.org/0000-0002-5989-0912
Yuanhong Zhao
Ocean University of China
Xiuying Zhang
Nanjing University
Songhan Wang
Nanjing Agricultural University https://orcid.org/0000-0002-8867-8486
Xuejun Liu
China Agricultural University https://orcid.org/0000-0002-8367-5833
Wen Xu
China Agricultural University
Ruotong Si
China Agricultural University
Keith Goulding
Rothamsted Research
Lei Liu (✉ liuleigeo@lzu.edu.cn)
Lanzhou University

Biological Sciences - Article

Keywords:

Posted Date: May 24th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2972121/v1

Additional Declarations: There is **NO** Competing Interest.

Farming the planet with better nitrogen use

Lei Liu[1,*], Wen Xu[2], Jia Ding[1], Pu Liu[1], Hang Xu[1], Sheng Liu[1], Ruotong Si[2], Xiankai Lu[3], Buqing Zhong[3], Yixin Guo[4], Xiao Lu[5], Yuanhong Zhao[6], Xiuying Zhang[7], Songhan Wang[8], Keith Goulding[9], Xuejun Liu[2,*]

[1]College of Earth and Environmental Sciences, Lanzhou University, Lanzhou 730000, China
[2]State Key Laboratory of Nutrient Use and Management, Beijing Key Laboratory of Farmland Soil Pollution Prevention and Remediation, College of Resources and Environmental Sciences, National Academy of Agriculture Green Development, China Agricultural University, Beijing 100193, China
[3]Key Laboratory of Vegetation Restoration and Management of Degraded Ecosystems, South China Botanical Garden, Chinese Academy of Sciences, Guangzhou 510650, China
[4]Laboratory for Climate and Ocean-Atmosphere Studies, Department of Atmospheric and Oceanic Sciences, School of Physics, Peking University, Beijing 100871, China
[5]School of Atmospheric Sciences, Sun Yat-sen University, Zhuhai 510275, China.
[6]College of Oceanic and Atmospheric Sciences, Ocean University of China, Qingdao 266100, China
[7]International Institute for Earth System Science, Nanjing University, Nanjing 210023, China
[8]Key Laboratory of Crop Physiology and Ecology in Southern China, Nanjing Agricultural University, Nanjing, 210095, China

[9]Sustainable Soils and Crops, Rothamsted Research, Harpenden, AL5 2JQ, UK

*Corresponding authors: Lei Liu, Lanzhou University. Tel &Fax: +86-0931-8912404, Email: liuleigeo@lzu.edu.cn; Xuejun Liu, China Agricultural University. Tel &Fax: +86-010-62733459, Email: liu310@cau.edu.cn

Abstract

Feeding an increasingly affluent population is a huge challenge facing global agriculture. In contrast to “large-scale farming” in developed economies (e.g. Europe and the United States), developing countries are dominated by “smallholder farms” relying on traditional farming practices but increasingly with substantial nitrogen overuse leading to severe environmental degradation and adverse human health. Here, we explore the potential for better nitrogen use by synthesizing the global relationship between farm size and nitrogen use for 16 major crops, assess the impact of farm size on nitrogen flows, and link these with air quality modelling to produce an integrated assessment of nitrogen-related environmental and health outcomes related to farm size. We find that increasing farm size in developing countries can contribute to more efficient and sustainable farming practices, which could decrease nitrogen overuse, ammonia emissions and nitrogen deposition by 20-25%, increase nitrogen use efficiency by 2-8%, and save over 142,000 premature deaths per year related to $PM_{2.5}$ air pollution. Although a large one-time investment is required for increasing farm size, there would be substantial progress towards achieving Sustainable Development Goals, associated with food security, a clean environment and improved human health.

Introduction

There are over 570 million farms worldwide, over half of which were less than two hectares in 2017[1,2]. These smallholder farms are mainly located in developing countries, while developed countries are dominated by large farms. Approximately 29-40% of global food is produced on smallholder farms[3], which are critical for eliminating poverty, inequality and hunger; a meta-analysis has suggested that smaller farms, on average, have higher yields and harbor greater crop and non-crop biodiversity at the farm and landscape scales than do larger farms[3]. However, small farms often overapply nutrients[4,5], and have been a critical constraint of innovations and agricultural transformation, while large farms are more efficient and productive, their size enabling the use of large machines with less labor[6,7].

Smallholder farms are, in particular, associated with nitrogen (N) overuse, posing an increasing threat of environmental degradation[8]. For example, China consumes 30% of global N fertilizer with a low N use efficiency (NUE) below 50%[9], indicating that over half of the N input is lost in the environment. Ammonia (NH_3) emissions, as a major N loss pathway, contribute to excessive N deposition in natural and semi-natural terrestrial and aquatic ecosystems and the formation of fine particulate matter ($PM_{2.5}$) air pollution. This causes direct economic losses through the waste of N fertilizer, contributes to soil acidification, biodiversity loss, freshwater and marine eutrophication, and threatens human health[10,11]. Small farms below two hectares are a key constraint to reducing N misuse, while large-scale farms can be a vital pathway to achieving environmental protection and Sustainable Development Goals (SDGs).

There is an increasing focus on developing sustainable farming, how scale, i.e. farm size, affects all aspects of sustainability, and how increasing farm size can increase yields on underperforming landscapes while simultaneously decreasing N pollution as compared to the view of some that small farms are more sustainable[3,4,6,11]. It is still unclear how farm size affects N fertilizer use efficiency in global crop production, whether it is feasible to implement large-scale farming in developing countries, and to what extent large-scale farming can mitigate N pollution. In this paper, we have compiled a high-resolution dataset of global cropland N budgets for 16 major crops, explored the impact of larger-scale farming on N fertilizer use, N use efficiency, and NH_3 emissions, and assessed the impact on fine particulate pollution ($PM_{2.5}$) and N deposition. We present a cost-benefit analysis of increasing farm size and the implications of this for achieving greener agriculture in developing countries.

Results

Nitrogen use vs. farm size for major crops

We first present the current global spatial distribution of farm size in 2017 based on the satellite-derived estimates using Google Maps and Bing Maps using the Geo-Wiki application (Supplementary Sect. 1.2). The categories of farm size include very large (>100 ha), large (16-100 ha), medium (2.56-16 ha), small (0.64-2.56 ha), and very small fields (<0.64 ha), as defined by Lesiv et al.[6] Globally, smallholder farms less than 0.64 ha comprised 46% of total farm numbers; farms less than 2.5 ha accounted for 57% of all farms (Fig. 1A). These smallholder farms mainly occurred in developing countries such as China, India and Africa. In China, smallholder farms (<2.5 ha) accounted for

94% of all farms, while medium (2.5-16 ha) and large farms (>16 ha) represented 4% and 2% of farms, respectively; India was also dominated by small farms (99%). In contrast, medium/large farms were mostly found in North America (98%), South America (82%), Western Europe (75%) and Australia (99%) (Fig. S1A).

We analyzed 16 major crops including rice, wheat and soybean, based on a recently updated geospatial dataset[9] to assess how the farm size affected N fertilizer use in 2017 (Fig. 1C and Fig. S2); Fig. 1C shows the global averaged crop-specific N application rates of each farm size category. Three crops (rice, wheat, and maize) accounted for around 70% of global N fertilizer use (Table S1). For any crop, N fertilizer application rate per unit area on large farms is usually less than that on small farms. For example, for rice, N fertilizer use on small-scale farms (137 kg N ha^{-1} yr^{-1}, <0.64 ha) was three times that on very large farms (>100 ha), and 1.58 times that on medium sized farms (2.56-16 ha). For maize, N fertilizer use on very large farms (>100 ha) was around 60 kg N ha^{-1} yr^{-1}, less than half that on small farms (> 130 kg N ha^{-1} yr^{-1}). Similar results were found for other crops including wheat, soybean and cassava, with the ratio of N fertilizer use on small farms to that on large farms being 1.5-3.

There are global hotspots of N use. N fertilizer use on the 16 major crops grown in the North China Plain and North India on small farms was more than 200 kg N ha^{-1} yr^{-1}, which was 2-4 times that on large farms in the United States and Western Europe. Large farms tend to apply less N per hectare and are often more efficient in their use of fertilizers because they use precision agriculture techniques (including the Global Positioning and mapping systems, sensors, remote sensing technologies, satellite imagery, variable rate application equipment, autonomous vehicles and drones)[4,7] to optimize fertilizer application rates and reduce N overuse.

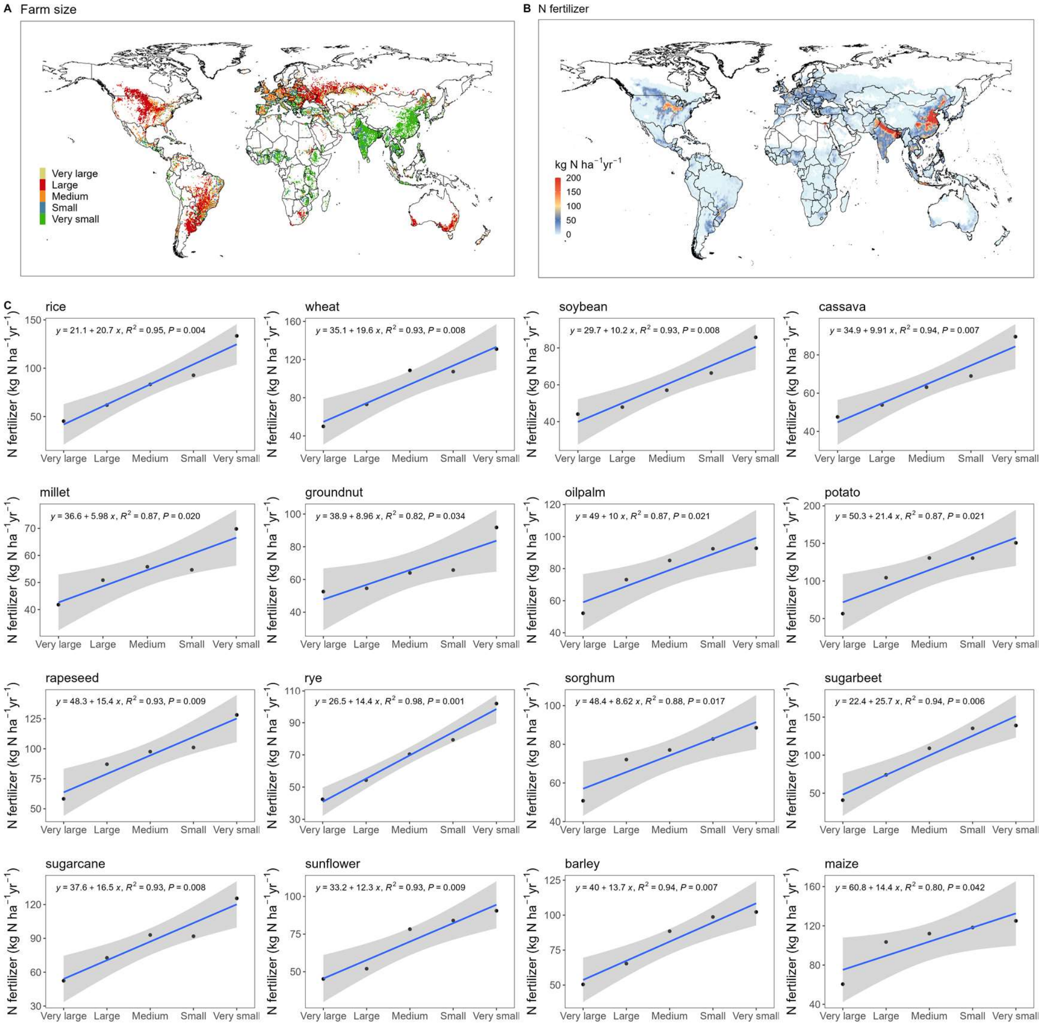

Fig. 1 N fertilizer use vs. farm size. A, the spatial distribution of farm size based on satellite-derived estimates using Google Maps and Bing and the Geo-Wiki application[5]. The categories are very large (>100 ha), large (16-100 ha), medium (2.56-16 ha), small (0.64-2.56 ha), and very small (<0.64 ha); B, the spatial distribution of N fertilizer use on 16 major crops. The spatial maps of N fertilizer use for each crop can be found in Fig. S2; C, the correlation of N fertilizer use with farm size for the crops.

Cropland N inputs and flows

Total global N inputs to croplands in 2017 were estimated at 193 Tg N yr^{-1}, of which synthetic fertilizer and manure accounted for 89% (172 Tg N yr^{-1}); the remaining 11% (21 Tg N yr^{-1}) came from 'the environment', i.e. biological N fixation, deposition from the atmosphere and irrigation (Fig. S3). High values of total N inputs were found in China (50 Tg N yr^{-1}), India (32 Tg N yr^{-1}), and the United States (18 Tg N yr^{-1}), which together comprised 52% of global N inputs. However, only 52% of this N was harvested in crops, corresponding to 101 Tg N yr^{-1}, while the remaining 48% was lost to the environment (NH_3, runoff and leaching, gaseous N_2O, N_2 and NO_x), amounting to an estimated 92 Tg N yr^{-1} based on the mass balance approach (Supplementary Sect. 1.1 and Fig. S4). Very low NUE was found in Asia (43-50%) where small farms dominate, while high NUE was found in European countries and North America (around 60-65%). In 2017, NH_3 emissions from 16 major cropping systems was estimated at 29 Tg N yr^{-1}, an important contributor to $PM_{2.5}$. Not surprisingly, high NH_3 emissions mainly occurred in areas with small farms (<0.64 ha), such as in the North China Plain and Northern India (>30 kg N ha^{-1} yr^{-1}). Two countries (China and India) with a large proportion of small farms accounted for 42% of global NH_3 emissions from cropping systems.

Impact of farm scale on N flows

The overuse of N fertilizer on small farms in developing countries can be overcome: the above results show that enlarging farm size is one way to reduce cropland N fertilizer overuse and NH_3 emissions, with implications for N deposition and $PM_{2.5}$-associated health impacts.

There is growing interest in increasing farm size in developing countries. In China and India, 79% and 98% of farms are on land with terrain slope of less than 10 degrees (Fig. S10), where farm size can be increased through consolidating farms[5,6]. Large-scale farming can be more efficient and sustainable, improving agricultural productivity by using advanced machinery, irrigation systems, and other technologies, and reducing the negative environmental impact of agriculture, while having the potential to boost economic growth in rural areas and increasing incomes. Historically, market transactions and institutional arrangements have facilitated farm consolidation; land banks have also been established to facilitate borrowing and lending of farmland in China[12].

Policies such as land reform, agricultural subsidies, and infrastructure development can play a critical role in supporting the expansion of farm size[7]. Governments could implement policies that facilitate land consolidation, provide incentives for farmers to increase their farm size, and improve access to markets and other essential services. Here we have considered the conservative estimates that: 1) the very-small farms (<0.64 ha) and small farms (0.64-2.5) are expanded to medium farms (2.5-16 ha); 2) medium farms are expanded to large farms (16-100 ha). This should be feasible and practical using current policy interventions, such as reform of land tenure. We did not consider the scenario of changing small farms to very large farms (>100 ha) due to the difficulty in consolidating land into large areas and associated high costs.

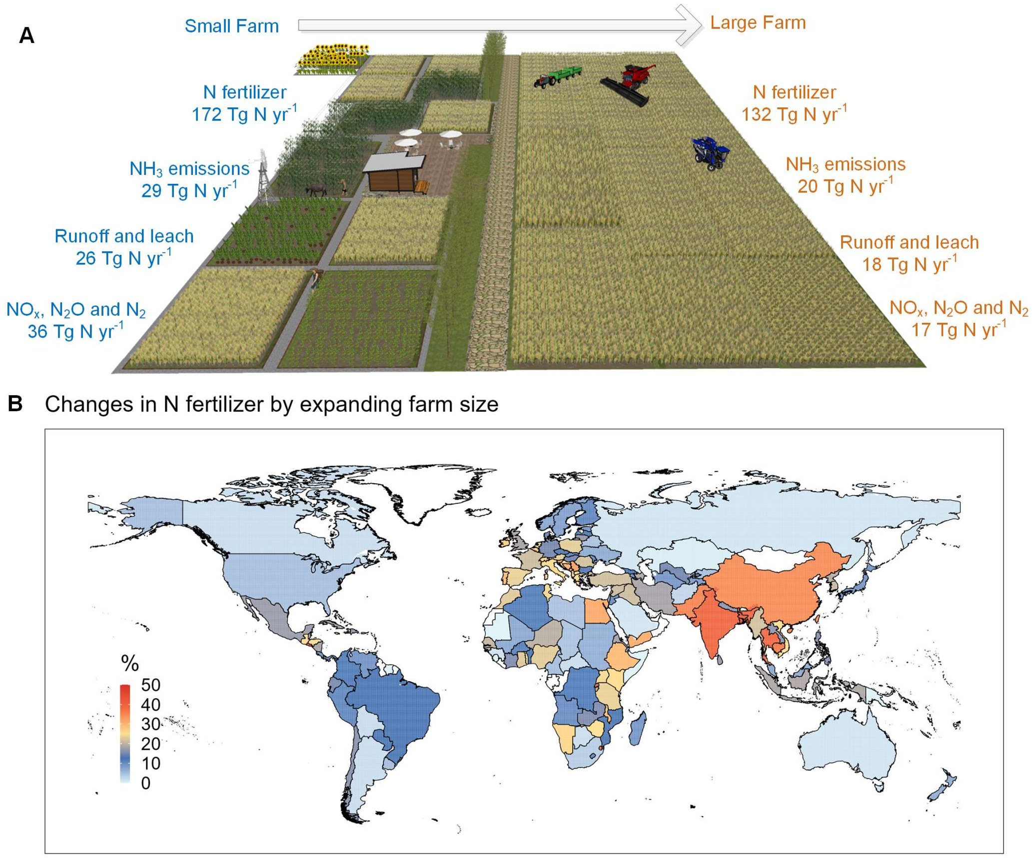

Fig. 2 Impact of increasing farm size on cropland N fertilizer use and N loss. A, a scheme for expanding small-medium farms to large farms; B, changes in N fertilizer use resulting from increasing farm size ([current fertilizer-new fertilizer] / current fertilizer, 100%).

Through expanding farm size, the number of small farms can be reduced from 58% to 12% globally, while farms above 16 ha would account for 88% globally (Fig. 2A). With the implementation of larger-scale farming, total N fertilizer use can be reduced by 23% from 172 to 132 Tg N yr^{-1}, with large decreases in China (35%, from 43 to 28 Tg N yr^{-1}) and India (39%, from 28 to 17 Tg N yr^{-1}) (Fig. 2B). Considering the impact on N inputs from the environment (fixation, deposition and irrigation), these would decline by 23% from 193 to 149 Tg N yr^{-1}, while the global NUE would increase by 5% (range

2-8%) from 52% to 57%, with a notable high increase in Asia from 45% to 53%. The increases in NUE would be accompanied by increased crop yields of 2-8% according to a study of expanding small farms below 0.1 ha to larger farms of around 7-60 ha in China[13]. It is easier to promote advanced technologies on larger farms, including the best management practices[14], while smallholder farms tend to have outdated production methods and high costs.

Besides the direct benefits of a decrease in N fertilizer use and an increase in NUE, our analysis shows that increasing farm size can also decrease substantial N losses while improving the environment and human health.

Decreased N losses: NH_3 emissions from cropping systems can be decreased by 23% globally by expanding farm size, with those in China and India declining by 33% and 39% respectively. Through expanding farm size, a 33% reduction of current N leaching and runoff losses can be achived globally (from 26 to 18 Tg N yr^{-1}), while cropland soil N_2O and NO_x emissions can be reduced by 47% (from 11.9 to 5.7 Tg N yr^{-1}) (Fig. S7). Regionally, large decreases occurred in Asia and Africa, exceeding 50% of total N leaching and runoff, and cropland N_2O and NO_x emissions.

Reduced health impacts: Millions of people die prematurely every year from diseases caused by $PM_{2.5}$ air pollution, partly associated with NH_3 and NO_x[11]. $PM_{2.5}$ was responsible for an estimated 3.9 million premature global deaths in 2017 (Fig. S9); this included over 1.3 million deaths in China, 1.0 million in India, and over 40000 in the United States. Agriculture contributed from 1-20% of premature deaths related to $PM_{2.5}$ pollution depending on the country, with a high percentage in the Europe Union (15-

20%), China and India (10-15%) and the USA (7-10%) (see Sect. 1.4 and 1.5 for the calculations). Expanding farming size can substantially reduce $PM_{2.5}$ pollution in eastern China (reductions of 5-10 μg m^{-3} yr^{-1}), followed by northeastern China and India (reductions of 0-5 μg m^{-3} yr^{-1}). In total, global premature deaths resulting from $PM_{2.5}$ can be reduced by 142,276 every year by reducing NH_3 emissions through increasing farm size (Fig. 2 and Fig. S9). For China and India, premature deaths can be reduced by over 63,000 and 27,000 per year respectively, followed by Indonesia, Bangladesh, Turkey, Pakistan and Russia (reductions of 2,000-6,700).

Decreased 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[9,15]. Global N_r deposition in 2017 greatly exceeded critical levels (to limit terrestrial biodiversity loss) (Fig. S12), 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} (Fig. S5), posing an increasing threat to ecosystems. Through increasing farm size, 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%) (Fig. S5). 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).

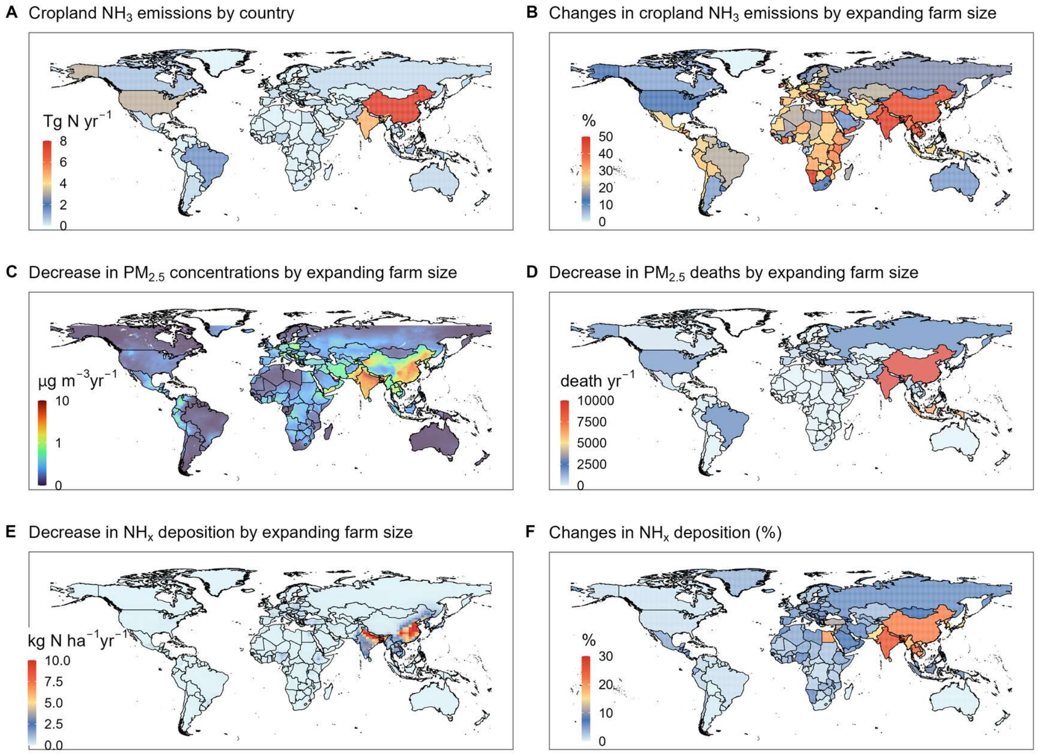

Fig. 3 Effect of increasing farm size on health impacts and N deposition. A, cropland NH_3 emissions by country; B, changes in cropland NH_3 emissions caused by increasing farm size; C, spatial distribution of changes in $PM_{2.5}$ caused by increasing farm size; D, spatial distribution of changes in premature deaths caused by increasing farm size; E and F, decreases in NH_x deposition caused by increasing farm size, and their changes (%) by country.

Cost-benefit analysis

Since the cost of expanding farm size is closely linked to economic development and land types[16], we divided the world into six categories including Low-income Plain (LP), Low-income Mountain plain (LM), Medium-income Plain (MP), Medium-income Mountain plain (MM), High-income Plain (HP), and High-income Mountain plain (HM) (Fig. S11C). The economic levels (GDP as USD Per Capita) were divided into three categories: High (>30,000 USD), medium (10,000-30,000 USD) and low (<10,000 USD), while the terrain was divided to: Plain (<1500 m and slope <10 degrees) and Mountain-Plain (>1500 m and slope <10 degrees) (Fig. S11D and Sect. 1.6 in SM). The costs of land consolidation in China were estimated as 2634, 3535, 3082, 3661, 3530, 3787 USD ha^{-1} for LP, LM, MP, MM, HP, and HM[7], respectively, while for other countries the costs were estimated and adjusted by the GDP per capita by country (Fig. S11).

The "*one-time investment*" for increasing farm size described above was around 1107 (976-1237) billion USD in 2017, mainly in China (385 billion USD) and India (358 billion USD). The estimated cost in China was slightly lower than that estimated by the Chinese Ministry of Natural Resources (400 billion USD) for the same degree of consolidation. China invested 12 billion USD and developed a land transfer system to increase farm size in 2020[12,13], but this was much less than the estimated costs of 385 billion USD for achieving a complete move to large-scale farming.

Despite the high cost of the *one-time* investment, we calculate that it is beneficial for farmers and society in general for decades or longer. A 23% decrease in the use of synthetic N fertilizer saves 13-23 billion USD *per year*, while reduced labor, machinery and associated services costs could save a further 26-36 billion USD *per year* (Fig. S12). Based on the willingness to pay (WTP) associated with reduced N-related environmental impacts (Supplementary Sect. 1.6), a net social benefit from reducing NH_3 emissions was around 18-28 billion USD *per year*, while savings from other environmental costs could be 11-21 billion USD *per year* for N leaching and runoff to water, N_2O and NO_x emissions. In addition, surface ozone concentrations could be also substantially reduced by reduced NO_x emissions resulting from implementing large-scale farming, such as in the NCP: a number of studies have estimated significant episodic surface ozone enhancement from soil NO_x emissions by up to 8 ppb when there is increased photochemical activity in the atmosphere[14,15]. Expanding farm size also facilitates sustainable agriculture, through the better use of machinery and knowledge exchange[7,16].

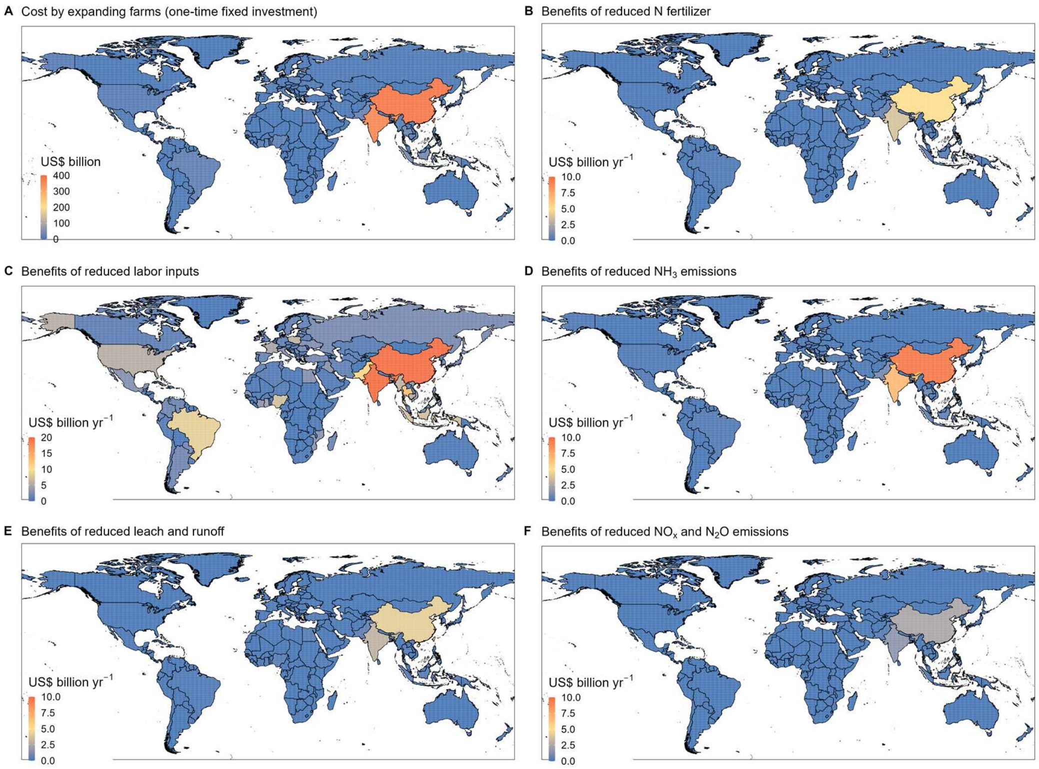

Fig. 4 Country-level *one-time* investments and *annual* benefits of increasing farm size.

A, estimated single fixed investment costs of land consolidation to increase farm size; B, annual benefits of reduced N fertilizer use resulting from increasing farm size; C, annual benefits of reduced labor resulting from increasing farm size; D, annual benefits of reduced NH_3 emissions caused by increasing farm size; E, annual benefits of reduced leaching and runoff caused by increasing farm size; F, annual benefits of reduced NO_x and N_2O emissions caused by increasing farm size. All as USD billions yr^{-1}.

Discussions

Currently, China and India are the two developing countries with the largest proportion of small farms of less than two hectares, which overuse of N fertilizers and so result in the most severe N pollution in the world. In contrast to developed countries with larger farms, N fertilizer use per hectare in China and India is 2-4 times that in high-income economies in the USA and Western Europe, where farms of more than 100 ha are common. Based on the conservative estimates above for China and India, reductions of around 30-40% in synthetic N fertilizer applied can be achieved by expanding farm size, which could decrease NH_3 emissions by 33-39%, NH_x deposition by 21-25% and $PM_{2.5}$ related deaths over 90,000 per year in China and India.

The reasons why farms in developed countries tend to be larger than those in developing countries involve social and economic factors. Developed countries generally have more access to capital and other resources (knowledge exchange, better machinery, etc) than developing countries, which can lead to economies of scale and increased efficiency. For example, large farms in developed countries have access to advanced technologies such as precision agriculture, which can help them to maximize yields and minimize inputs[7,18]. Larger farms are able to negotiate better prices for inputs and products, reducing costs and increasing profits. In contrast, many developing countries face challenges such as limited access to credit, lack of access to modern agricultural inputs, and underinvestment in infrastructure[19]. Governments need to formulate appropriate policies to promote urbanization, improve education and skills among rural populations, strengthen urban-rural economic connections, create more job and entrepreneurial opportunities for farmers, and gradually shift rural labor to urban areas. This will help to reduce the labor supply in the agricultural sector and promote the gradual development of larger-scale agriculture.

This has occurred in developed countries. For example, American farm sizes have gone through a process of expansion, restriction and re-expansion[19], in which the government has played an important role with continuous interventions. Except during the two world wars, the USA's farm scales have increased and by the 2010s, the midpoint (medium) farm size had increased to 408 ha[19]. The US government has used 3S (Remote **S**ensing, Geographic Information **S**ystems, and Global Positioning **S**ystems) technology to develop precision agriculture, promoting this on farms and accelerating the reorganization and merger of small farms to large farms. This *"American path"* may prove an important reference for developing countries to expand farm scales for achieving the increasing food demand while decreasing N-related environmental and health impacts.

The movement of labor away from agriculture is now common in rapidly developing countries, leading to a shortage of labor on small farms. However, with rapid urbanization, economic development and successful industrialization, the shifting of the economy from agriculture to nonagricultural sectors in China and India has proved advantageous. In addition, the global population is ageing at an increasing rate[20], which could also lead to labor shortages on small farms. A comprehensive transformation of smallholder farming to a more sustainable agriculture is urgently needed to overcome the ageing of the rural population in developing countries, especially in China and India. To reduce labor costs, farmers need to replace labor with machinery. Labor inputs on middle-large scale farms can be reduced to one person per ha in contrast with around six people per ha for small farms[7,11]. Large-scale farming can provide a breakthrough for improving rural living standards and achieving ‘modern’ agriculture. If farm sizes cannot be changed in the future, China and India could become gigantic importers of food grains due to a shortage of labor and the difficulty in mechanizing in small farms. This has already happened in Japan and Republic of Korea[21].

Due to the social, economic and environmental differences across countries, the extent of large-scale farming varies, but a move towards larger-scale farming is the pathway towards agricultural modernization. The smooth transfer of farmlands from smallholder farmers to larger farmers is essential for achieving sustainable agriculture in developing countries. Farm size expansion has occurred in China since the 2000s via a cropland transfer system[22], accompanied by particular developments[23-26]; first, machinery service providers directly rent the land of small farms, helping to consolidate fragmented farmlands; second, local governments facilitate farmland rental arrangements and have introduced subsidies for mechanization. In 2014, the China’s central government issued “Opinions on Guiding Orderly Transferring of Rural Land Management Rights, and Developing Appropriate Scale of Agricultural Operations” to accelerate and standardize cropland transfers. To increase the scaling up of farms in developing countries, government policies and institutional incentives must be developed, such as improving infrastructure construction, promoting agricultural technology development, transferring surplus rural labor, increasing agricultural subsidies and developing agricultural funds, credit and insurance.

References

1. Galloway, J.N. et al. Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. Science 320, 889-892 (2008).
2. Lowder, S.K. et al. The number, size, and distribution of farms, smallholder farms, and family farms worldwide. World Dev., 87, 16-29 (2016).
3. Ricciardi, V. et al. Higher yields and more biodiversity on smaller farms. Nature Sustain., 4, 651-657 (2021).
4. Wu, Y. et al. Policy distortions, farm size, and the overuse of agricultural chemicals in China. Proc. Natl. Acad. Sci. USA, 115, 7010-7015 (2018)
5. Senapati, N. et al. Global wheat production could benefit from closing the genetic yield gap. Nat. Food, 3, 532-541 (2022)
6. Lesiv, M. et al. Estimating the global distribution of field size using crowdsourcing. Glob. Chang. Biol., 25, 174-186 (2018).
7. Duan, J.K. et al. Consolidation of agricultural land can contribute to agricultural sustainability in China. Nat. Food 2, 1014-1022 (2021)
8. Liu, X.J. et al. Enhanced nitrogen deposition over China. Nature 494, 459-462 (2013).
9. Liu, L. et al. Exploring global changes in agricultural ammonia emissions and their contribution to nitrogen deposition since 1980, Proc. Natl. Acad. Sci. U.S.A 119,

e2121998119 (2022)

10. Chen, X. et al. Producing more food with lower environmental costs. Nature 514, 486-489 (2014).
11. Wang, S. et al. Urbanization can benefit agricultural production with large-scale farming in China. Nat. Food 2, 183-191 (2021)
12. Huang, J. et al. The prospects for China's food security and imports: will China starve the World via imports? J. Integr. Agric. 16, 2933-2944 (2017).
13. Yu, Y. et al. Reforming smallholder farms to mitigate agricultural pollution. Environ. Sci. Pollut. Res. 29, 13869-13880 (2022)
14. Wang, R.; Bei, N.; Wu, J.; Li, X.; Liu, S.; Yu, J.; Jiang, Q.; Tie, X.; Li, G., Cropland nitrogen dioxide emissions and effects on the ozone pollution in the North China plain. Environ. Pollut. 294, 118617 (2022).
15. Lu, X.; Ye, X.; Zhou, M.; Zhao, Y.; Weng, H.; Kong, H.; Li, K.; Gao, M.; Zheng, B.; Lin, J.; Zhou, F.; Zhang, Q.; Wu, D.; Zhang, L.; Zhang, Y., The underappreciated role of agricultural soil nitrogen oxide emissions in ozone pollution regulation in North China. Nature Communications 2021, 12, 5021.
16. Cui, Z. et al. Pursuing sustainable productivity with millions of smallholder farmers. Nature 555, 363-366 (2018).
17. Xu, W. et al. Quantifying atmospheric nitrogen deposition through a nationwide monitoring network across China. Atmos. Chem. Phys. 15, 12345-12360 (2015)
18. Grinsven V. et al. Costs and benefits of nitrogen for Europe and implications for mitigation. Environ. Sci. Technol. 47, 3571-3579 (2013).
19. James M. et al. Farm size and the organization of USA report summary from the Economic Research Service (2013), https://www.ers.usda.gov/webdocs/publications/45108/39359_err152.pdf

20. Ren, C.C. et al. Ageing threatens sustainability of smallholder farming in China. Nature. 616, 96-103 (2023)

21. Otsuka, K. Food Insecurity, Income Inequality, and the Changing Comparative Advantage in World Agriculture. Agricultural Economics 44: 7–18 (2013)

22. Huang, J. and Ding, J. Institutional Innovation and Policy Support to Facilitate Small-Scale Farming Transformation in China. Agricultural Economics 47: 227–237 (2016)

23. Ren, C. et al. The impact of farm size on agricultural sustainability. J. Clean. Prod. 220, 357-367 (2019)

24. Ma, X. et al. Assessment of high-standard farmland construction fund effectiveness in China. Statist. Decision 36, 85-89 (2020).

25. Liu, H. Accelerate the implementation of a new round of plans for high-standard farmland and improve the quality of construction throughout the year. Agric. Integr. Develop. China 3, 23-28 (2021).

26. Li, L., Wu, L. The impact of rural population changes on food security in China. J. China Agric. Univ. Social Sci. 37, 80-91 (2020).

Methods

Here we provide a brief introduction to the methods used in this study, but detailed information is in the Supporting Information. To assess the potential impact of expanding farm size on N pollution, we first compiled global N budgets in 2017, including N fertilizer use, manure use, and the environmental N inputs (biological N fixation, N deposition and irrigation) for 16 major crops, and their outputs including crop N uptake, NH_3 emissions, leaching and runoff, and other gaseous emissions (N_2O,

NO_x and N_2). Given the constructed N budgets, we made a global evaluation of how farm size affected N fertilizer use for 16 major crops and its impact on N use efficiency and NH_3 emissions from croplands. Fractional N_r deposition and $PM_{2.5}$ concentrations as affected by expanding farm size were modeled using an advanced atmospheric transport model (GEOS-Chem). We used the satellite-derived $PM_{2.5}$ exposure estimates and the fractional $PM_{2.5}$ as affected by increasing farm size to estimate $PM_{2.5}$ related premature deaths following the Global Burden of Disease (GDB) methods. Finally, we estimated the potential cost and benefits from increasing farm size at the country level.

Acknowledgments This study was supported by the National Natural Science Foundation of China (42001347, 41471343, 42277097, and 41705130), the Chinese State Key Research & Development Program (2017YFC0210100 and 2017YFD0200101), and the High-Level Team Project of China Agricultural University (X. Liu). The analysis in this study is supported by the Supercomputing Center of Lanzhou University. **Author contributions** L.L. and L.X.J. designed the research; L.L. and L.X.J. wrote the draft; L.L., L.S., and X.H. performed the analysis and prepared the figures; All co-authors contributed to the text and interpretation of the results. **Competing Interests** The authors declare no competing financial interests. **Data and code availability** The GEOS-Chem model code is open source at https://doi.org/10.5281/zenodo.3676008. All study data are included in the article and/or the supporting information.

Supplementary Files