
Wang, Chen; Duan, Jiakun; Ren, Chenchen; Liu, Hongbin; Reis, Stefan; Xu, Jianming; Gu, Baojing. 2022. **Ammonia emissions from croplands decrease with farm size in China**. *Environmental Science & Technology*, 56 (14). 9915-9923. https://doi.org/10.1021/acs.est.2c01061

Ammonia emissions from croplands decrease with farm size in China

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Abstract:

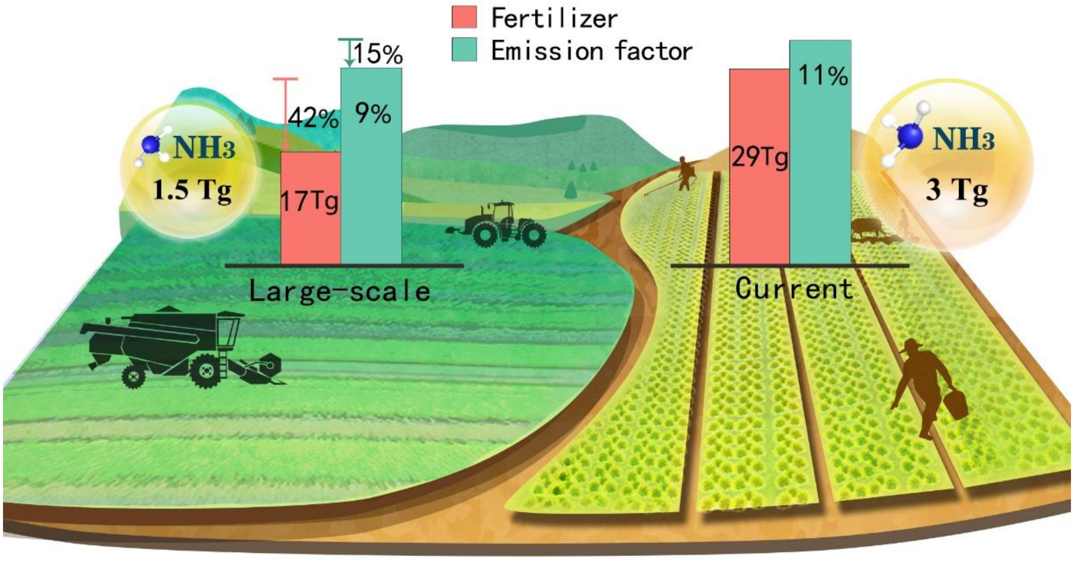
Farm size affects nitrogen fertilizer input and agricultural practices, which are key determinants of ammonia (NH_3) emissions from croplands. However, the degree to which NH_3 emissions are associated with changes in farm size is not well understood yet despite its crucial role in achieving agricultural sustainability in China, where agricultural production is still dominated by smallholder farms. Here we provide a first analysis of the relationship between farm size and NH_3 emissions based on 863,000 surveys conducted in 2017 across China. Results show that NH_3 emissions (kg ha^{-1}) on average decrease by 0.07% for each 1% increase in average farm size. This change occurs mainly due to a reduction in nitrogen fertilizer use and the introduction of more efficient fertilization practices. The largest reduction in NH_3 emissions is found in maize, with less pronounced changes in rice cultivation, and non for wheat production. Overall lower NH_3 emissions factors can be observed in the north of China with increasing farm size, especially in the northeast, the opposite pattern was found in the south. National total NH_3 emissions could be approximately halved (1.5 Tg) in a scenario favouring a conversion to large-scale farming systems. This substantial reduction potential highlights the potential of such a transition to reduce NH_3 emissions, including benefits from a socioeconomic point of view as well as for improving air quality.

Key words: Farm size; Ammonia emissions; Agriculture; Crops; Fertilizer use

Synopsis

Increasing farm size is critical to mitigate NH_3 emissions by reducing nitrogen fertilizer input and changing fertilization practices.

TOC:



Introduction

Ammonia (NH_3) plays an important role in the anthropogenic impacts on the global nitrogen (N) cycle; however, substantially increased NH_3 emissions as a consequence of intensive use of synthetic fertilizers have well-documented negative impacts on ecosystem and human health, contributing to environmental problems including air pollution, soil acidification, eutrophication and biodiversity loss[1-3]. To safeguard food security, China uses one-third of the world production of synthetic N fertilizers on its croplands, which only account for below 9% of global total agricultural area.[4] Over-use of N fertilizers leads to a large amount of NH_3 emissions from croplands, accounting for about 30-40% of the total NH_3 emission in China.[5, 6] With population growth and increasing affluence and better living standards, N fertilizer use and its NH_3 emissions from croplands are projected to continue to increase unless mitigation measures are introduced.[7, 8] One such measure is optimizing N fertilizer use, which would both help to reduce economic cost and agricultural NH_3 emissions, while maintaining a sufficient level of plant nutrient inputs for crop growth, thus achieving a triple benefit of maintaining food security, economic efficiency gains and environmental protection.[9, 10]

China's agriculture is dominated by smallholder farms.[10] It has been documented that small-scale farming typically leads to substantial over-use of fertilizer.[11, 12] The "Action Plan for the Zero increase of synthetic fertilizer use" launched in 2015 and the "Clean Air Action", updated in 2018, both committed to reducing NH_3 emissions from agricultural systems.[13, 14] Advanced fertilization methods such as described by the "4R" of nutrient stewardship (Right amount, Right timing, Right fertilizer type, and Right placing) and soil testing have been developed; however, they are difficultly applied at the smallholder level due to constrains related to the small farm size.[15, 16] Fertilizer use per hectare would be projected to decrease with the increase of farm size due to the changes of agricultural practices enabled by the larger-scale farming operation.[15, 17] For example, smallholder farmers prefer non-fixed inputs such as synthetic fertilizer and pesticides to generate yield increase, while larger farm operations tend to increase the use of fixed inputs, such as machinery and irrigation, due to their scale effects.[11] However, the mechanisms of how and to what extent potential changes in farm size can affect NH_3 emissions from croplands is not yet well understood.

In this paper, we explored the impact of farm size on NH_3 emission in croplands in over 2,800 counties in China. First, the relationship between farm size and NH_3 emissions was analyzed at national scale; second, the analysis focused on how farm size affects NH_3

emissions in various crops and field management practices, as well as identifying the impact of both natural and socio-economic factors affecting NH_3 emissions; third, future changes of NH_3 emissions in croplands were projected taking into consideration large-scale farming in China, based on modelling both changes in N fertilizer use and NH_3 emissions per N fertilizer use in all counties.

Data and methods

Data sources

Data on farm size, fertilizer use, and management practices were collected from the Second National Pollution Census across China in 2017, providing a unique data source including approximately 863,000 field surveys conducted in over 2,800 counties. The spatial origin of survey data is depicted in Figure S1. It comprises general information on the field (planting area, location and planting mode), crop information (crop name, farming and irrigation methods, crop yield, straw yield and recycled amounts in each season), and fertilization (fertilization time, type, amount, nutrient content and fertilization method in each season). Statistical information about each province is provided in Table S1. All synthetic fertilization rates are converted into N application rates according to the N content of the specific fertilizers applied. To eliminate extreme values and reduce estimation errors, we excluded outliers of main variables in the data less than 3% quantile and greater than 97% quantile. The precise geographical coordinates of each field were recorded in the census datasets and allowed for the generation of high-resolution distribution maps of fields included in the survey. Statistical analyses were conducted at a county scale to derive the average farm size of each county. In addition, soil and meteorological information of each county was compiled based on a map with 1 km × 1 km spatial resolution to represent the information of each survey field. Climate data for each county were obtained from the China Meteorological Data Web (http://data.cma.cn/) and Fick and Hijmans[18]. Soil pH and clay content were obtained from the Harmonized World Soil Database[19] and Resource and Environment Science and Data Center (http://www.resdc.cn/data.aspx?DATAID=264).

Emission calculation

Ammonia emissions are known affected by agricultural practices, climate and soil factors.[20-22] In order to calculate the NH_3 emissions from fertilization, fertilizer type, fertilization time, fertilizer application rate, fertilization method and crop type are included in the calculation. We divided crop types covered in the survey data into four categories: wheat, corn, rice and others. Fertilizer types are divided into synthetic fertilizer (Syn_fer), organic fertilizer (Org_fer), and controlled-release fertilizer (CRF). Fertilization methods include deep fertilization (Deep), irrigation after deep fertilization (Deep_water), topdressing (Top) and irrigation after topdressing (Top_water). Here, we use the average temperature of the month to represent the fertilization temperature at that time. Based on the empirical NH_3 emission model we developed [23], NH_3 emissions from each fertilization can be calculated using Eq (1):

$$Ln(y) = \alpha + \sum_i \beta_i X + C_1 Croptype + C_2 Fertilizertype + C_3 Mode + \varepsilon \qquad (1)$$

where y represents accumulated emissions (kg NH_3 ha^{-1}), X stands for the potential explanatory variables, here including the fertilizer application rate (Nrate), clay (%) and temperature, α, β and C represent the model coefficients, which is listed in Table S2, ε is model error, detailed explanations can be found in Wang et al.[23]

The emission factor (EF) in each county is calculated by computing the weighted average of all the surveyed plots using Eq (2):

$$EF_{i,j} = \sum_{i,j}^{n} \frac{y_{i,j}}{Nrate_{i,j}} / n_{i,j} \tag{2}$$

where *EF* represents the emission factor (%), *y* stands for accumulated emissions (kg NH_3 ha^{-1}), *Nrate* stands for the fertilizer application rate (kg NH_3 ha^{-1}), *n* refers to the number of surveyed plots, *i, j* represent the individual counties and crop types.

Scenario analyses

China's croplands are not naturally fragmentated, because most of the croplands are located in the plains, which are physically suitable for large-scale farming. China has potential to consolidate 86% of its cropland area into a large-scale farming regime with an average farm size >16 ha to reduce N fertilizer input and improve mechanization to reduce N losses.[24] To explore the impact of large-scale farming on NH_3 emissions, we estimated changes of NH_3 emissions assuming the large-scale farming potential is achieved in China, based on mapping croplands at a 30 m × 30 m spatial resolution for geostatistical analysis.[25] Detailed information on large-scale farming in China can be found in Duan et al.[24] Data on fertilizer use of 2,853 counties in 2017 was collected based on the city-level Statistical Yearbooks, and for data that could not be obtained from there, province-level statistical yearbook data was allocated based on the proportion of cultivated land area. All city-level statistical yearbooks are available at http://data.cnki.net/yearbook/. The predicted N total fertilizer use and emission factor in each county under the large-scale farming (LF) scenario is calculated as follows:

$$Y_i^{Predicted\ LF} = \exp\left(\beta \cdot Ln\ X_i^{Current} - \alpha \cdot Ln\ X_i^{With\ LF}\right) \cdot Y_i^{Current} \tag{3}$$

Y represents the synthetic fertilizer application rate used in *i* county. *X* stands for the farm size (ha), α refers to estimated coefficients of large-scale farming from Duan et al.[24]

$$EF_{ijt}^{Predicted\ LF} = \exp\left(\beta \cdot Ln\ X_i^{Current} - \beta \cdot Ln\ X_i^{With\ LF}\right) \cdot EF_i^{Current} \tag{4}$$

$$E_i = \sum_i EF_i \cdot Y_i \tag{5}$$

where *EF* represents emission factor (%) in *i* county, *E* represents the emission volume (in kg NH_3) in *i* county, *X* stands for the farm size (ha), *β* represent the estimated coefficients in Fig. 1.

Results and Discussion

Emissions as a function of farm size

NH_3 emissions per unit area decrease with the increase in farm size at national scale (Fig. 1, Table S3). The results show that NH_3 emission factors are typically higher in small-scale farms in the south; in contrast, NH_3 emission factors are lower in the large-scale farms in the north, especially in the northwest (NW) and northeast (NE) of China. This opposite pattern is also more obvious in terms of provinces level (Fig. S2), The high emission factors in South China (SC) are strongly affected by high temperature and multiple crop cycles per year. Multiple cropping systems typically require a higher N fertilization rate and are therefore subject to NH_3 emission rates and emission magnitudes.[23, 26] Meanwhile, small-scale farms in the south are more suitable for manual topdressing of fertilizer in the hilly, while in large-scale farming in the north it is feasible to apply more advanced fertilization methods in the plain areas.

In Guangdong and Guangxi provinces in South China, the average farm size is between 0.3 and 0.9 ha, with NH_3 emission factors as high as 16% and 18%, respectively (Table S4). Tropical fruits and vegetables are commonly cultivated in South China with the most common fertilization method being topdressing (Fig. S3, S4). The high air temperature in south China also benefits the increase of NH_3 emission. For example, sugarcane is mainly planted in Guangxi with a high fertilization rate, leading to the high NH_3 emission intensity. Average farm sizes in Northwest China are quite large, e.g. Inner Mongolia and Xinjiang, are 7.2 and 3.9 ha, with widespread utilization of advanced agricultural practices such as mechanical operation leading to comparatively low NH_3 emission factors of 8.5% and 8.3%, respectively.

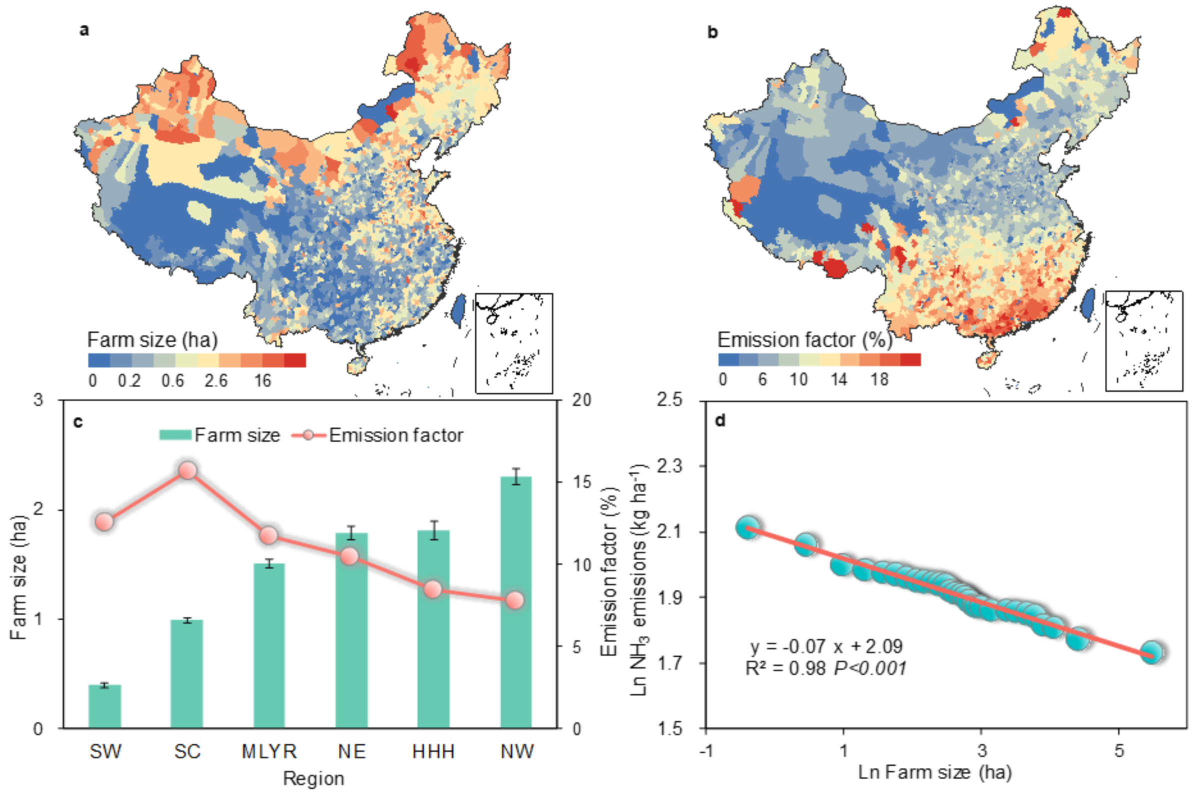


Figure 1. Farm size and emission factor in 2017 in China. (a) Average cropland farm size in

each county; (b) Emission factor in each county; (c) Comparison of farm size and emission factors in each region; (d) Changes of cumulative NH_3 emission with farm size. The farm size in each county is averaged across all survey plots, and the emission factor is calculated by applying the ERMA model based on Wang et at.[23], considering the fertilization rate, fertilization type and fertilization method of different crops in each county. Error bars in (c) represent the standard errors. Data in Fig. 1d have been log-transformed, and farm size is divided into 29 groups, with each data point representing an average value of a certain farm size group. The number of farms in each farm group used for the analysis is shown in Table S5. For the abbreviations of all place names and the provinces included in each agricultural area, see Appendix Table S5.

With the increase in farm size, the amount of fertilizer per hectare (kg ha^{-1}) and the NH_3 emissions per N fertilizer application (kg ha^{-1}) are decreasing. Statistically, a 1% increase in farm size is associated with a 0.07% decrease in NH_3 emissions overall (Fig. 1d). Higher income due to increased profitability in large-scale farms enables the increased utilization of modern technologies and management practices, which in turn benefit N use efficiency and reduce of NH_3 emissions.[15] Advanced agricultural management practices, such as irrigation and mechanization, are invested in more readily by large-scale farms, and farmers on these farms typically have better agricultural knowledge and skills, applying these to improve agricultural labor productivity and the use efficiency of agricultural inputs.[27, 28]

Emissions in different crops

In this paper, crops were divided into four categories (rice, wheat, maize and other crops) and the relationship between NH_3 emissions and farm size for each crop type was analyzed. NH_3 emissions from all crops decrease with the increase of farm size except for wheat (Fig. 2). Wheat mainly uses base fertilizer and less topdressing during the growth period. The fertilization mainly occurs in the autumn and spring while air temperatures are low, and the average temperature difference between base fertilizer and topdressing is small (12.4 - 13.4 °C). Currently, wheat farms have the largest average farm size among all crop farming types (2.4 ha), with deep placement of fertilizers being the prevalent application method (Figs. 3a, 4a). All these factors contribute to a lower NH_3 emission rate observed for wheat farming. Unlike other crops that are distributed in both the north and south, the geographical distribution of wheat farming is mainly concentrated in the North China Plain. NH_3 volatilization of different farm sizes is less affected by climate and fertilization practices, resulting in little change in the relationship between the farm size and the NH_3 volatilization (Fig. 2b).

Substantial reduction in NH_3 emissions in maize is found with the increase of farm size. In addition to summer maize in the North China Plain, a large amount of spring maize is planted in Northeast and South China, which is a wide gap in the geographical location of maize planting. Summer maize needs topdressing during the growth seasons, e.g. at the 12-leaf stage, and hence temperature when fertilization is applied is typically high with an average of 17.8 - 22.4 °C. Although for some crop rotations, such as rice-wheat or wheat-corn, the fertilization methods and time required for both crops on the same size farmland are different. Since maize is planted in different locations across the country at various season of the year, the more obviously difference between fertilization times with temperature and the size of farms could be analyzed. The average farm size of maize farms is also the smallest compared with other crops (Fig.3a). In the South, e.g. in Sichuan and Yunnan provinces, the limited utilization of advanced fertilization methods on mostly small farms, in combination with high air temperatures, results in high NH_3 emissions. In Northeast China, spring maize is planted on large-scale farms and fertilizer is often applied in one-time deep application regimes (Fig.S3). Therefore, these factors indicate that farm size has the largest relative impact on NH_3 emissions in maize farming.

Ammonia emissions of rice and other upland crops also decrease with the increase in farm size, which are primarily found in the hilly areas in the South. Rice planting is concentrated in the Middle and Lower Yangtze River (MLYR) and broadcasting is the most commonly applied fertilization method. The proportion between topdressing vs. deep application is about 7:3 (Figs. S3, S4). Other crops, including other food and cash crops, are distributed fairly evenly across the country.

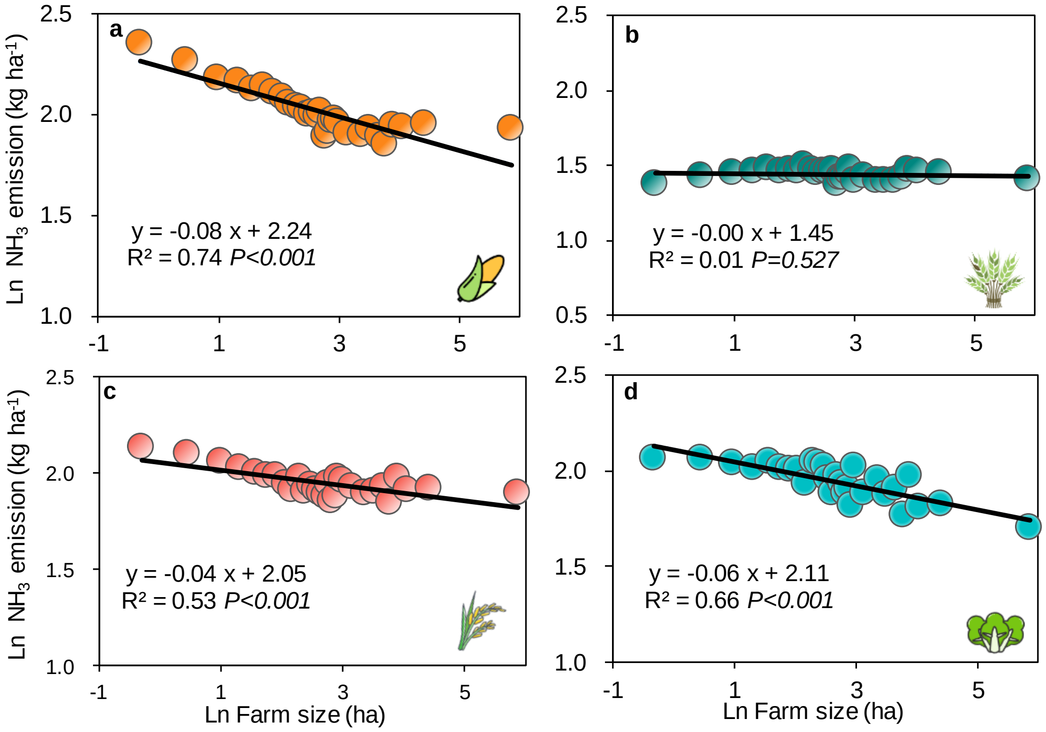


Figure 2. Farm size and NH_3 emissions of different crops. (a) Maize; (b) Wheat; (c) Rice; (d) Other crops. The abscissa is the grouping of farm size, which have been log-transformed, each data point represents an average value of a certain farm size group. And the number of farms in each farm group used for the analysis is shown in Table S7. These icons in the figure are from the Iconfont, which holds a third-party open copyright: https://www.iconfont.cn/ (the same below).

Field management with farm size

Small rural household-based farms with both crop planting and livestock raising (CPLR) tend to apply more organic fertilizer, which reflects a more traditional agricultural development mode of self-sufficiency.[29] Manure would be returned to own croplands to provide nutrient input. However, the share of CPLR households has declined sharply in recent years, with increasing numbers of farmers seeking part-time employment in urban areas and tending to overuse chemical fertilizers as an “insurance” to avoid yield losses while investing less time in the farming activities.[10, 30] Figure 3a show that the average farm size which applying synthetic fertilizer and controlled-release fertilizer is comparatively more prevalent than the application of organic fertilizer. The larger the average farm size, farmers are more willing to invest in advanced agricultural machinery, young and efficient labor force, and then choose more efficient fertilizer types, including slow-release compound fertilizers and organic-inorganic compound fertilizers. The proportion of synthetic fertilizer (81%) is the highest compared to other fertilizer in China (Fig. 3b), and there is no clear direction of change with an increase in average farm size (Fig. S6c). The application of organic fertilizer decreases gradually with the increase of farm size, but when the scale increases to a certain extent, the application proportion will increase, mainly because large farms apply more processed and relatively high-quality organic fertilizer, which can improve soil fertility. Compared to the medium-scale farms, small and large-scale farm has a higher proportion of organic fertilizer (Fig. S6c) with the total proportion of organic fertilizer used in China is 12%.

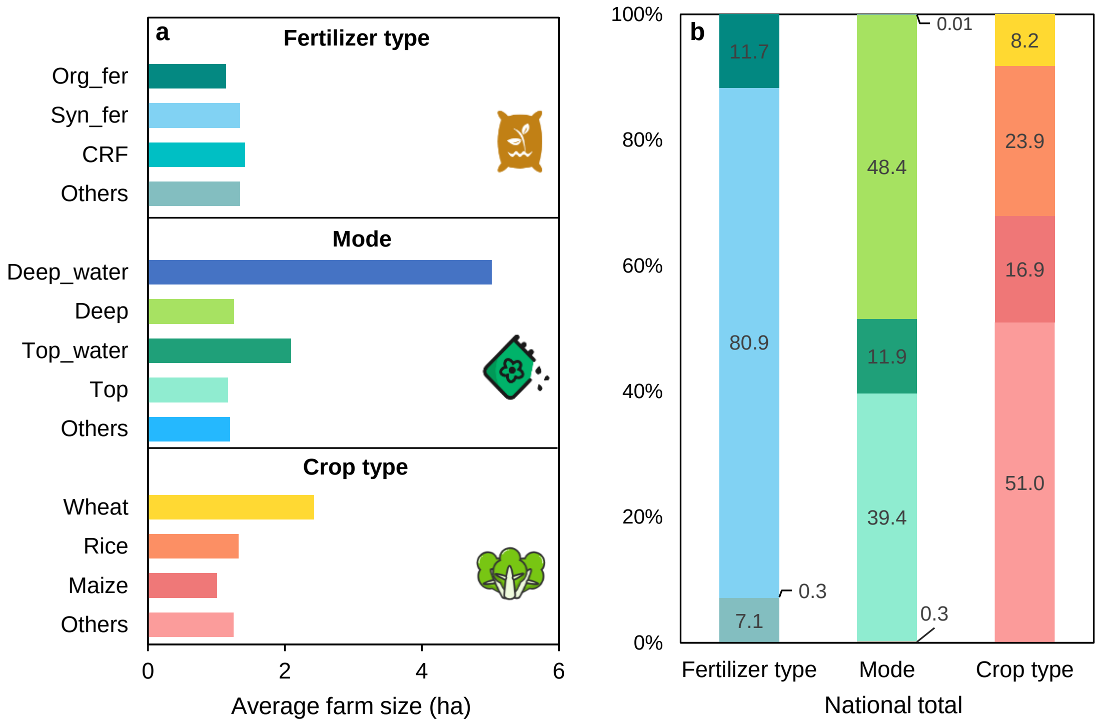


Figure 3. Agricultural practices under different farm size. (a) Average farm size in relation to different fertilization types, modes and crop types; (b) The proportion of different farming characteristics in China, the numbers in the figure represent the proportion; Syn_fer: synthetic fertilizer; Org_fer: organic fertilizer; Syn & Org: mixture of organic and synthetic fertilizer; CRF: control released fertilizer; Top: broadcasting fertilization; Top_water: irrigation after broadcasting or broadcasting before rainfall. Deep: deep placement of fertilizers. Deep_water: irrigation after deep placement.

The change in farm size has substantial impacts on agricultural management practices.[10, 11] The average farm size of farms applying two different fertilization methods, i.e., topdressing with water and deep application with water, is significantly larger than that of farms applying other methods (Fig. 3a, 4b). It also proves that more machinery and better irrigation facilities such as sprinklers or drip systems will invest to relatively large-scale farmers to meet the nutrient requirements for crop production, which contribute to the increase of N use efficiency (NUE), reduce NH_3 emissions and bring long-term profits.[31, 32] Novel agricultural technologies such as accurate layered fertilization techniques reduce soil compaction and allows for the placement of fertilizers at different depths to reduce the overall amount fertilizer used and improve NUE as fertilizer nutrients are better accessible to plants, compared to broadcasting.

In small-scale cropland farming, hand broadcasting accounts for a larger proportion of fertilizer application. With an increase in farm size, the proportion of broadcasting decreases (Fig. S6a), while irrigation after topdressing increases. Fertilization combined with irrigation is a common way adopted by farmers to improve NUE and reduce NH_3 emissions. Smallholder farms usually rely on rain-fed or traditional pumped well irrigation systems. In most cases, these irrigation systems will be operated inefficiently, which will wash away a large amount of fertilizer and result in higher than average fertilizer losses. However, in contrast, large-scale farms utilize more fixed infrastructure can be invested, and irrigation facilities such as sprinkler or drip can improving both water and fertilizer use efficiencies.[32]

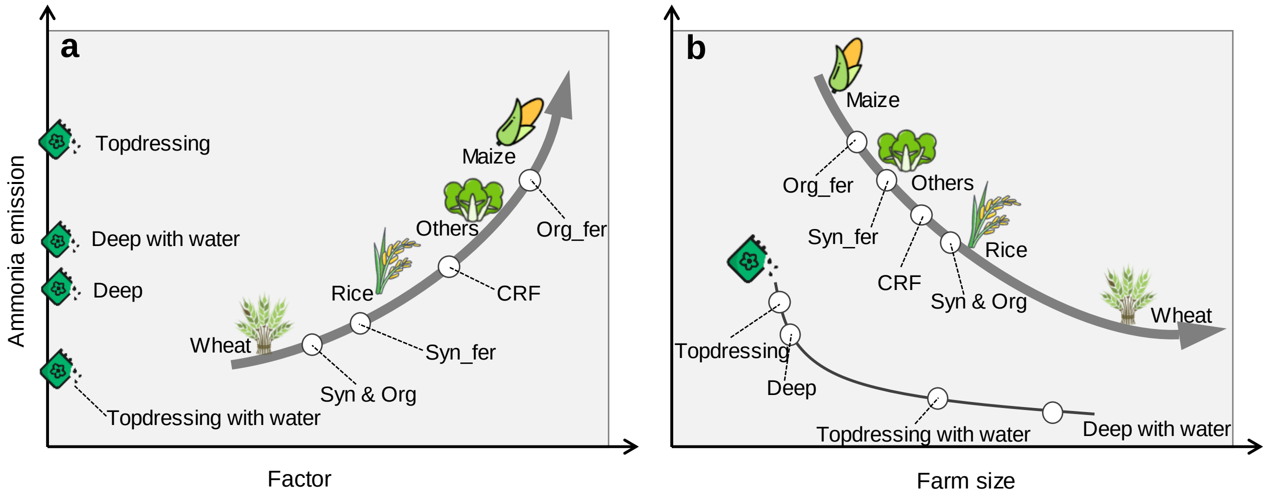


Figure 4. Driving factors of NH_3 emission in croplands. (a) Effect of crop type, fertilizer type and fertilization mode on NH_3 emissions, the priority of each factor in the figure is based on our previous study[23]; (b) Effect of farm size on NH_3 emissions through the three major driving factors in (a), with the order based on Fig. 3.

A series of advanced land management technologies have been developed to improve NUE; however, these technologies are rarely implemented at smallholder scale due to socioeconomic barriers related to farm size.[9, 16] For example, soil testing and leaf N sensors have been demonstrated the capability to significantly reduce N inputs while increasing NUE. However, the adoption rate of such advanced methods by Chinese smallholders is extremely low due to the high implementation cost per hectare of frequent in-situ field monitoring and low direct economic benefits. Farmers with larger cropland scale, (e.g., alternative farming models and cooperation farming) have high profits, younger workforce and more willing to try new technologies and better management approaches on their farms.

Reducing NH_3 emissions through large-scale farming

More than 70% of Chinese cropland is managed by smallholders, and only a small share of croplands is managed by farms of a size larger than 16 ha. These large-scale croplands are mainly distributed in Northeast China and northwest Xinjiang, Inner Mongolia and a small part in North China Plain (Fig. S7a). NH_3 emissions in the north are significantly lower than those in the south, with the national average emissions per ha being 11% (Table S4). The fertilization method proportion of broadcast by hand in south China such as Jiangxi, Guangdong and Guizhou are 77%, 63% and 66%, respectively, while the proportion in north China such as Inner Mongolia and Xinjiang are 12% and 7%, respectively (Fig. S3). This is mainly due to the lack of mechanical investment on small-scale cropland compared with the north. By using geostatistical analysis, we estimate that over 80% of the croplands in China could be consolidated into large-scale farms with an average farm size larger than 16 ha (Fig. S7b). Regionally, farm size could be increased substantially in Sichuan Basin, Northeast China and North China Plain, to farm sizes even above 100 ha in some areas. However, due to topographic limitations, small-scale croplands will likely remain the dominant farming type in Guangzhou and Yunnan and coastal Fujian Province.

In a large-scale farming scenario, total N input to Chinese croplands would be reduced by 12 Tg (Fig. 5c), while the application of animal manure to croplands would increase due to better coupling of livestock-cropland systems. The reduction of N fertilizer application mainly occurs in regions, where large-scale farming is feasible, such as Sichuan province (where N fertilizer use could be reduced by more than 50%, Table S8). The decrease in N fertilizer application is a result of an increase in mechanization, e.g. increased use of deep placement using machinery in large-scale farming, leading to reduced NH_3 emissions. The overall NH_3 emission factor would decline by 9.3% nationwide under the large-scale farming scenario. Total NH_3 emissions from croplands could hence be reduced by 1.5 Tg, accounting for 49% of total cropland NH_3 emissions (Fig. 5f).

China still faces challenges in implementing a large-scale farming scenario in terms of land tenure and the *Hukou* system.[17] Land consolidation requires a large amount of financial investment, e.g. for the removal of ridges, footpaths, ponds, paddy levees and other non-cultivated lands.[33] Although it may have long-term benefits at societal level and to farmers, the one-of investment required is still a significant barrier. While this may prevent a full implementation in the short term, it may be realized through unifying agricultural operations e.g. through land service rental, which could present an interim solution to a full-scale implementation of large-scale farming with the aim to mitigate NH_3 emissions. Land service rental could also reduce the fixed input costs per hectare of cropland without introducing profound changes to the land tenure and *Hukou* system, and it could help to improve the uptake of mechanization.[16]

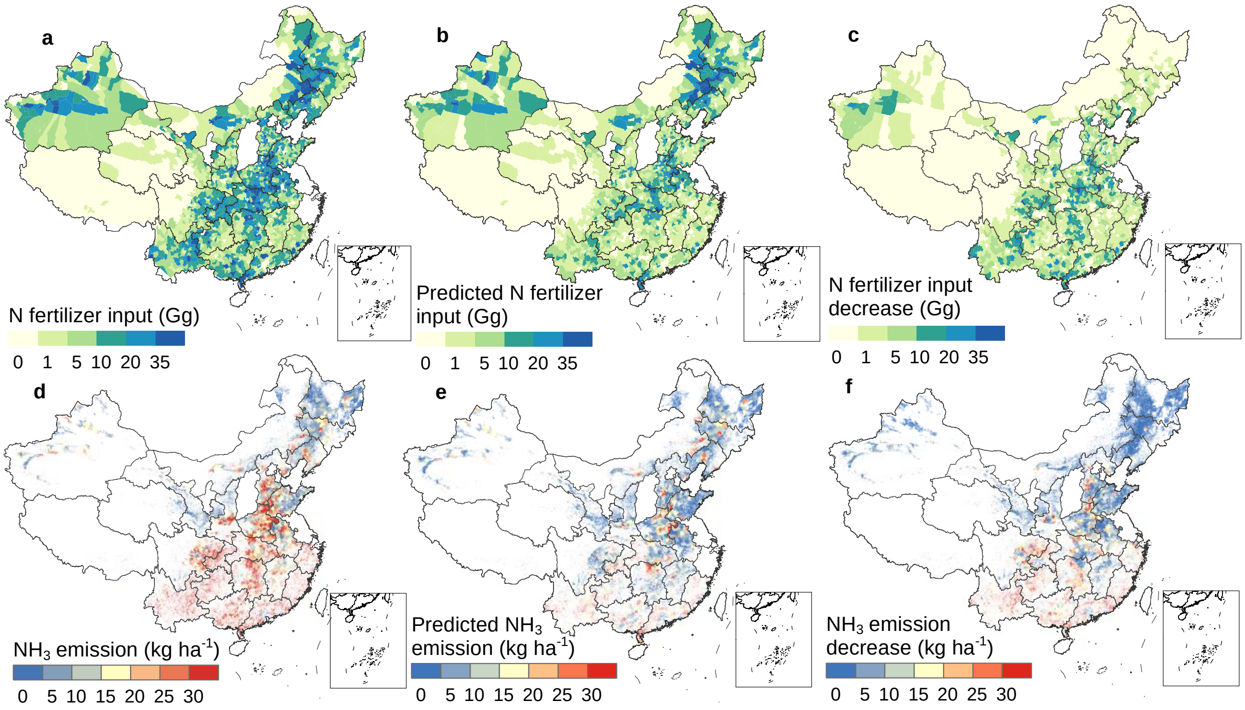


Figure 5. Changes of N fertilizer input and NH_3 emission between current level and large-scale farming scenario. (a) Current N fertilizer input in 2017; (b) Predicted N fertilizer input under a large-scale farming scenario; (c) N fertilizer input reduction; (d) Current NH_3 emissions in 2017; (e) Predicted NH_3 emissions under a large-scale farming scenario; (f) NH_3 emission reduction. The predicted values are based on the geographical potential for the introduction of large-scale farming. The changes result from the differences between predicted and current values. Average changes across different provinces are provided in Supplementary Table S8. (1Gg=10^9g)

Socioeconomic barriers and limitations

Currently, research on options for the reduction of NH_3 emissions from cropland mainly focuses on technical innovations for optimizing fertilizer use, but socioeconomic constraints are not well understood. In order to reduce non-point source pollution, China implemented a

“Zero increase of synthetic fertilizer use” objective in 2015, covering precision fertilization, adjusting the use structure of synthetic fertilizer, improving fertilization methods and organic fertilizer substitution. However, Chinese agriculture is dominated by smallholder farming with traditional fertilization methods being the cause of a substantial losses of nutrient N to the environment via NH_3 emissions. As we have established that farm size has an impact on NH_3 emissions, such measures and investments would not be effective if applied to smallholder farms. Efforts from different stakeholders including government, scientists, enterprises and farmers are required to promote the expansion of farm size, which will reduce the use of synthetic fertilizer, improve fertilization technology and reduce NH_3 emissions.

Due to the Household Contract Responsibility System (HCRS) in China, cropland is divided into 4-5 pieces to safeguard that both high- and low-quality lands are allocated to each rural household in a fair manner. In addition, the relative difference between the cost of synthetic fertilizers and the revenue generated from crops means that overall the cost of fertilizer to farms is a minor factor, which is also one of the main reasons for overuse of fertilizer.[17] With the urbanization process in China, a large number of rural laborers migrate for a non-agricultural job in cities, which would cause a substantial change on the income structure of rural households.[34] Such small farmers tend to apply more synthetic fertilizers to ensure crop yield and use the simplest and inefficient fertilization methods to minimize investment to grain the maximum benefits, but potentially leading to decline in the NUE, increase in fertilizer loss and NH_3 emission. Large-scale farms or family farms with high agricultural income are more willing to try new technologies and advanced measures.[15]

Therefore, to improve the NUE, it is necessary to provide knowledge-transfer and incentives to farmers from a socio-economic perspective. Increase farm size and subsidies to attract young labors with the agricultural knowledge and skills to return to rural areas, focus on agricultural management, and reduce the application of synthetic fertilizer and NH_3 emission.

At the same time, the proportion of farms run by small rural households with both crops and livestock would be gradually reduced. Typically, large-scale livestock farms are located far away from croplands, leading to long-distance transport of manure.[29, 35] Although organic fertilizers are very efficient providers of nutrients, odour of unprocessed manure and high transportation cost are difficult to be accepted by farmers. Therefore, the decoupling between small cropland farms and livestock is also the main reason for the reduction of manure recycling, leading to a large amount of nutrient and NH_3 emission losses to the environment. More efforts to spatially co-locate livestock farms and thus integrate livestock farms in cropland areas would improve the reuse of manure in croplands, which could not only reduce NH_3 emissions of those croplands, but also the NH_3 emissions from livestock production overall.

Competing interests

The authors declare no competing interests.

CRediT authorship contribution statement

Chen Wang: Software, Formal analysis, Methodology, Writing – Original Draft, Visualization. **JiaKun Duan:** Visualization, Formal analysis. **Chenchen Ren**: Software, Methodology. Formal analysis. **Hongbin Liu:** Resources, Data curation. **Stefan Reis:** Writing – Review & Editing. **Jianming Xu:** Writing – Review & Editing. **Baojing Gu:** Conceptualization, Formal analysis, Writing – Original Draft, Funding acquisition.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (42061124001).

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