https://doi.org/10.5194/essd-2022-263
Preprint. Discussion started: 22 August 2022

Historical nitrogen fertilizers use in China from 1952 to 2018

Zhen Yu[1,2], Jing Liu[2], Giri Raj Kattel[3,4,5]

[1] Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters (CIC-FEMD), Nanjing University of Information Science & Technology, Nanjing, China 210044

[2] Institute of Ecology, School of Applied Meteorology, Nanjing University of Information Science and Technology, Nanjing, 210044, China

[3] School of Geographical Sciences, Nanjing University of Information Science & Technology, Nanjing, China

[4] Department of Infrastructure Engineering, University of Melbourne, Parkville, Melbourne, Australia

[5] Department of Hydraulic Engineering, Tsinghua University, Beijing, China

Correspondence to: Zhen Yu (zyu@nuist.edu.cn)

Abstract. China ranks the highest position on the nitrogen (N) fertilizers consumption in the world. Although the N fertilizers use has greatly contributed to the China's food production, this has also caused unprecedented alteration in the biogeochemical cycles and endangered terrestrial and aquatic ecosystems. Existing use of N fertilizers in China as shown by digital maps are usually coarse in resolution, and intermittently covered with biasedly gridded dataset. Here, we have reconstructed a historical, annual N fertilizers use dataset in China at 5 km × 5 km resolution covering the period of 1952 to 2018 by integrating improved cropland maps. Results showed that the most of the N input was directly applied as N-only fertilizer, while the contribution from compound fertilizers ranged between 16% and 24% since 1980. The national total N fertilizers input increased from 0.06 Tg N yr^{-1} (0.05 g N m^{-2} yr^{-1}) in 1952 to 31.15 Tg N yr^{-1} (18.83 g N m^{-2} yr^{-1}) in 2014, then decreased to 28.31 Tg N yr^{-1} (17.06 g N m^{-2} yr^{-1}) in 2018. Despite the total N input decreased by 9.1% (2.84 Tg N yr^{-1}) from 2014 to 2018, the N input from compound fertilizers increased by 6% (0.43 Tg N yr^{-1}) during the corresponding period. The previous FAO-data-based N fertilizer products in China overestimated the N use in low, but underestimated in high cropland coverage areas. However, our newly reconstructed data have not only corrected the existing biases and improved the spatial distribution but also showed vegetable and other crops (orchards), but not grain crops, are the most intensively fertilized crops in China, implying the importance of quantifying greenhouse gas (GHG) emissions from these croplands. We argue that the reconstructed, spatially-explicit N fertilizers use data in this study are expected to contribute to better understanding in biogeochemical cycles including the simulations of GHG emission and food production in China. The cropland dataset is available via an open-data repository (https://doi.org/10.6084/m9.figshare.20402490.v1) (Yu, 2022).

1 Introduction

The birth of the Haber-Bosch technique has converted enormous amount of unreactive nitrogen (N) to reactive forms greatly alleviating N limitation in the agricultural production (Galloway et al., 2004; Sutton and Bleeker, 2013; Erisman et al., 2008; Lu and Tian, 2017). However, the excessive N fertilizers use in crops has become a global issue as this has caused unprecedented alteration of terrestrial and aquatic ecosystems. Since the introduction of synthetic N fertilizers in China in the early 1910s, its use has markedly increased along with population growth and agricultural intensifications. Today, China ranks highest in producing and using the reactive N for food and fiber production (Naughton, 2006; FAOSTAT database, 2018). About 30% of global N fertilizers was applied in China's cropland in 2017 alone, which accounted for about 9% of the global cropland areas (FAOSTAT database, 2018; Yu et al., 2021). Despite such high intensity of N fertilizers use, the crop yields in China were lower compared to the global average (Wang et al., 2020b; FAOSTAT database, 2018). Former study reported an increase of N fertilizers use by over 2.7 folds from 1977 to 2005, while the marginal contribution of N fertilizers to food production was declining, e.g. the large increment of N fertilizers use helped enhance grain yields by only 98% (Ju et al., 2009). Both field-based and modeling studies evidenced the widespread, over-use of N fertilizers in China, and it has been advocated that reducing N fertilizers use would not be adversely affecting the crop production (Zhu and Chen, 2002; Ju et al., 2009; Tian et al., 2012; Huang et al., 2008). Reduced N fertilizers use has implications for minimal food-production costs and higher environmental benefits including the reduced water-borne pollution and greenhouse gas (GHG) emissions (Kahrl et al., 2010).

One of the direct benefits of reducing the N fertilizers use in cropland has been reported as the reduction in the N_2O emission – a GHG with global warming potential as high as 298 times greater than that of CO_2 over a 100-year time horizon (Myhre et al., 2013). China is currently the largest N_2O emitters worldwide, in which agriculture alone has contributed to 64% (Shang et al., 2019; Zhou et al., 2014), implying the potential of N_2O emission reduction via optimization of N fertilizers use in cropland (Tian et al., 2012). Moreover, the reduced N fertilizers use in cropland also helps alleviate soil acidification and eutrophication further benefitting the terrestrial and aquatic environments (Strokal et al., 2016). A better understanding of the spatial-temporal distribution of N fertilizers use in China's cropland will help locate the hot-spot of N surplus and eventually contribute to the management including the efficient use and optimization. However, N fertilizers use in China has greatly varied spatially and temporally with disparity in the dataset to capture the historical N fertilizers use. Most existing spatio-temporal dataset depicting N fertilizers use in croplands of China are irregular and relatively coarse. For example, the N fertilizers use dataset are available in both international and national archives. The International Fertilizer Industry Association (IFA) and the Food and Agricultural Organization (FAO) which have archived the amount of annual N fertilizers consumption at national level since 1961, while the National Statistical Bureau of China has archived the amount of annual N fertilizers use at both national and provincial levels since 1987. Some attempts were made to spatialize the national level N fertilizers use, but the products were still relatively low in spatial resolution (e.g. 0.5 degree for Lu and Tian (2017)). Many process-based modeling studies simulated the impacts of N fertilizers use on biogeochemical cycles in China using the low-resolution N fertilizers dataset, which greatly impaired the reliability of the estimations (Tian et al., 2012; Wang et al., 2020a). There is an

https://doi.org/10.5194/essd-2022-263
Preprint. Discussion started: 22 August 2022

urgent need for a long-term, spatial explicit N fertilizers dataset to serve the quantification of national and global GHG budgets, and to benefit data analyses and the environment protection including reduced water pollutions and improved land-based ecosystem functions.

In this study, we have reconstructed the annual N fertilizers use in China's cropland using various statistical records, reports, and gridded images at 5 km × 5 km resolution covering the period of 1952 to 2018. We aimed to: 1) develop a continuous dataset depicting the N fertilizers use in cropland in China; and 2) examine the historical distributions and shifts of N fertilizers use cropland in China. Our focus is on the chemical, rather than the organic N fertilizers use, and the term 'N fertilizers' we have adopted here is to refer exclusively to synthetic N fertilizers.

2 Data and methods

2.1 Reconstruction of the national and provincial N fertilizers use

This study focuses on N fertilizers use in the mainland China, while Taiwan, Hong Kong, and Macaw were excluded due to no data availability. The dataset we have adopted here for synthetic N fertilizers use in cropland of China was from N-only fertilizers, and N-mixed fertilizers or 'compound fertilizers'. We have adopted two different phrase and units to differentiate the N fertilizers use at national level i.e. 'N fertilizers input' (Tg N per year), and crop field level i.e. 'N fertilizers use rate' (g N per unit land per year).

We first reconstructed the total N fertilizers input in China's cropland at national level. The national fertilizer inputs were provided by both FAO (https://www.fao.org/faostat) and the National Bureau of Statistics of China (Chinese Statistical Yearbook (CSY); also available from https://data.stats.gov.cn). Specifically, the FAO data provides the total N input in China from 1960 to 2018. While in comparison, the CSY data describes total fertilizers use (including N, phosphate, potassium fertilizers such as ammonium phosphate) covering the period of 1952 to 2018, and the N-only fertilizers (e.g. ammonia, ammonium nitrate) from 1987 to 2018. The national total N fertilizer input of the period 1960 to 2018 was directly obtained from the FAO, while the ratio of N fertilizers to the total fertilizers was used to derive the total N fertilizers use from 1952 to 1959.

Second, we compiled the N fertilizers used in each province in China. For the period 1987-2018, N fertilizers use was directly derived from the CSY database. For the period 1952 to 1986 when the provincial data was unavailable, the reconstructed national N fertilizers use was allocated to each province based on the provincial N proportions derived in 1987.

2.2 Reconstruction of the crop-specific N fertilizers use rate in each province

We examined the major crops planted in China and grouped them into 10 types, including early rice, mid-season rice, late rice, wheat, corn, soybean, oil seeds, cotton, vegetable, and other crops. Specifically, other crops include barley, sorghum, sugarcane, tobacco, fruits (e.g. apple, pear, citrus). The N fertilizers use rate for each major crop types (except other crops) was intermittently reported in the Cost-benefit Report of the National Agricultural Products (CBR) covering the period of 2004-

https://doi.org/10.5194/essd-2022-263
Preprint. Discussion started: 22 August 2022

2018 (Table 1). The CBR data provides officially released fertilizers use information summarized from thousands of samples collected in each province in China. Both temporal and spatial gap-filling approaches were implemented for the period of 2004-2018. Temporal gap-filling was applied in province with N fertilizers use rates intermittently reported in few specific years. To do so, the missing N fertilizers use rates in the province were linearly interpolated using the two nearest data reported before and after the year. Spatial gap-filling was applied in province with N fertilizers never reported for the crop type(s), in which two fertilizers use scenarios were considered. For the first scenario, we assumed that the N fertilizers use rate of the crop in the province was the same as the average rate at national level. While for the second scenario, we assumed that the N fertilizers use rate of the crop in the province was the average of the rates adopted in nearby provinces.

For the period of 1981 to 2004, the N fertilizers use rates were calculated from the N inputs and the planted areas of each crop type in each province. While for the period of 1952 to 1980 when provincial, crop type-specific N fertilizers use data were unavailable, we proportionally adjusted the N fertilizers use rate of each crop type based on the ratio of N fertilizers use in the year and the amount used in 1981. This is assuming that the change of N fertilizers use rate of a crop is proportional to the change of the total N fertilizers use in the province.

As pointed out in the section 2.1, the total N input includes two components, i.e. N from compound fertilizer and N-only fertilizer. Unfortunately, CSY database documented the use of compound fertilizers in major crop types but the N ratio was not specified. Since the N ratio varied between 16%-33.33% in compound fertilizers according to the major fertilizers used in China (http://fgw.kaifeng.gov.cn/info/2107), we assumed two extreme scenarios that the N ratio were either 16% or 33.33% for compound fertilizer being applied to each major crops.

In addition, N fertilizers use in vegetables were also highly uncertain. Specifically, various vegetables were planted in China, while the N fertilizers use rates were missing for the most of the vegetables. However, the vegetables received much higher N fertilizers (71.9 g N m^{-2}) than non-vegetable crops according to the former published study (Huang et al., 2017). In general, the total fertilizers applied in vegetable was about 3.3 times higher than the recommended application rate (Huang et al., 2017). Therefore, two additional scenarios were considered in reconstruction of the N fertilizers use in vegetables. In the first scenario, we assumed that the N fertilizers use rate in vegetable was the same as the average of all other major crop types. In the second scenario, we assumed the N fertilizers use rate in vegetable was 3.3 times of the average rate of other major crop types.

After the gap-filling of the nine of the ten major crop types (except other crops), the total N inputs were calculated by multiplying the rates and the areas of each crop type in each province. The provincial residue N inputs (the difference of the total N inputs calculated, and the total N inputs derived from the FAO and the CSY) were allocated to other crops and the N fertilizer rates were calculated by dividing the residue N inputs to the planting areas obtained from the China Agricultural Yearbook (Table 1).

https://doi.org/10.5194/essd-2022-263
Preprint. Discussion started: 22 August 2022

Table 1. Datasets used for nitrogen (N) fertilizers use reconstruction.

Datasets	Year	Resolution	Variable	Sources
Cropland distribution maps	1900–2016	Annual, 100m-5km	Cropland distribution	(Yu et al., 2021)
China Agricultural Yearbook (CAY)	1980–2018	Annual, provincial	Planted areas of each major crops in each province	National Bureau of Statistics of China
China Statistical Yearbook (CSY)	1952–2018 1987–2018	Annual, provincial	Total fertilizer N fertilizer	National Bureau of Statistics of China
Cost-benefit Report (CBR)	2004-2018	Intermittently, provincial	N fertilizers use by crop types in each province	National Development and Reform Commission of China (Price Department)
FAO N fertilizer	1960-2018	Annual, national	Total nitrogen fertilizers use in China	(FAOSTAT database, 2018)
Rotation maps	1980, 1990, 2000, 2002, 2011	County-level	Crop rotation information	(Liu et al., 2018)

2.3 Approach for spatializing N fertilizers use

Before the N fertilizers use rate could be allocated spatially, a crop type map is required. Here, we reconstructed crop rotation maps from 1952 to 2018 using the model we previously developed (Yu and Lu, 2018; Yu et al., 2019) (see Figure S1 for the details). Reconstruction of annual crop rotation map can be divided into two periods, namely the periods before and after 1980. For the period of 1980-2018, county-level crop rotation maps in 1980, 1990, 2000, 2002, and 2011 were used (Table 1) (Liu et al., 2018). More specifically, when allocating a crop type in a province for a year from 1980, the cropland grid-cell located in a county was given priority to be assigned to the crop type identified from the nearest-year rotation map. Due to the lack of data, the crop rotation map in 1980 was used for the period before 1980.

Based on the 100-m crop rotation maps developed in the previous step, we link the crop type and the N fertilizers use rate developed for each crop types in each province. Specifically, we spatialized the N fertilizers use rate for each year using the 100-m crop type maps. For grids with multiple crops cultivated in a year, the fertilizers use rate was the total N fertilizers use of all crops (i.e., total N fertilizer applied in a grid-cell in a year). The 100-m resolution N fertilizers use rate maps were then resampled to 5 km × 5 km for a comparison and analyses. The methodology flowchart is showed in Figure 1.

https://doi.org/10.5194/essd-2022-263
Preprint. Discussion started: 22 August 2022

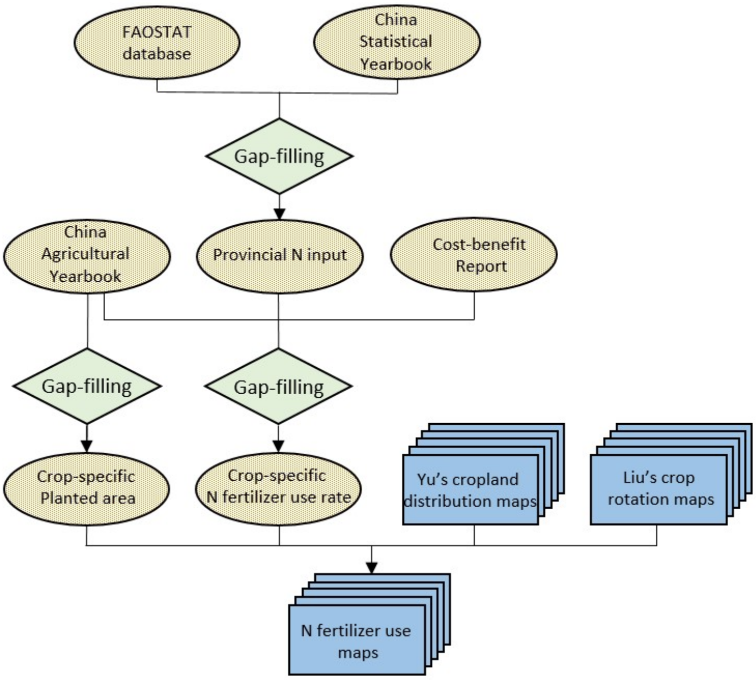


Figure 1. Methodology flowchart of nitrogen (N) fertilizer map reconstruction

3 Results

3.1 National nitrogen fertilizers use for crop production in China

The compiled national total N fertilizers use increased from 0.06 Tg N yr^{-1} in 1952 to the peak of 31.15 Tg N yr^{-1} in 2014 then decreased to 28.31 Tg N yr^{-1} in 2018. The majority of the N input was directly applied as N-only fertilizers (e.g. urea, ammonium carbonate), while the contribution from compound fertilizers (e.g. ammonium phosphate) increased from 16% in 1980 to 24% in the 2010s. Despite the total N input decreased by 9.1% (2.84 Tg N yr^{-1}) from 2014 to 2018, the N input from compound fertilizers increased by 6% (0.43 Tg N yr^{-1}) during the corresponding period (Figure 2).

The rising N fertilizer input was consistent with the N fertilizers use rates (per square meter of cropland), which increased from 0.05 g N m^{-2} yr^{-1} in 1952 to 18.83 g N m^{-2} yr^{-1} in 2014, then decreased by 9.4% from 2014 to 17.06 g N m^{-2} yr^{-1} in 2018 (Figure 2).

https://doi.org/10.5194/essd-2022-263
Preprint. Discussion started: 22 August 2022

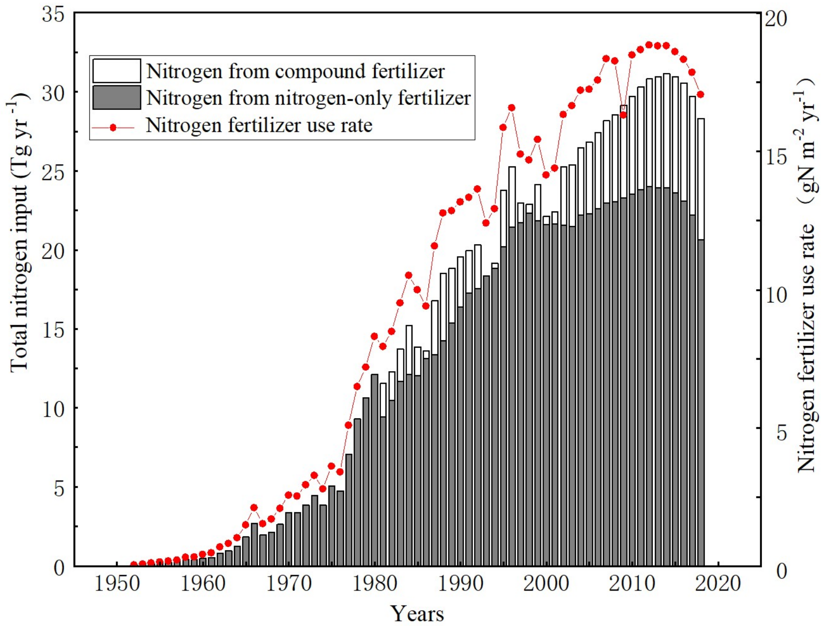


Figure 2. Total nitrogen fertilizers input and the average nitrogen fertilizers use rate in China's cropland from 1952 to 2018

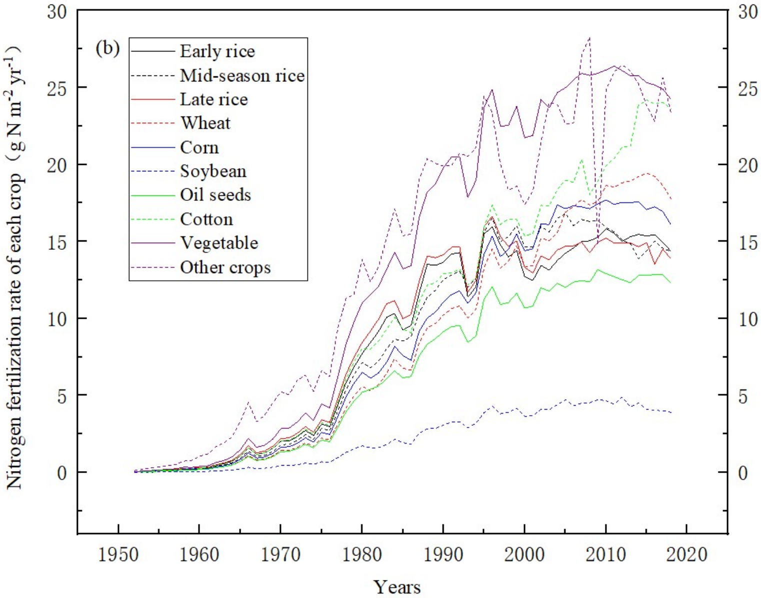
3.2 Nitrogen fertilizers use by crop types in China

We examined the N fertilizers use in each of the major crop types planted in China since 1952 (Figure 3 is the average of different scenarios; the different scenarios were showed in Figure S2&3). The N fertilizers use rates were very low in 1950s and increased to 10-25 g N m^{-2} yr^{-1} in most crop types (Figure 3). Among all the crop types, soybean received the lowest N inputs with the rate below 5 g N m^{-2} (Figure 3). In comparison, extremely high N fertilizers use was observed in other crops (55-70 g N m^{-2} yr^{-1} in 2010s, Figure 3). Besides, vegetable received substantial amount of N fertilizers as high as 26 g N m^{-2} yr^{-1} in the 2010s then slightly decreased to 24 g N m^{-2} yr^{-1} in 2018 (Figure 3). The N fertilizers used rate in rice (i.e. early rice, mid-season rice, late rice) increased from the 1950s then leveled off in the mid-1990s, and the N fertilizers use rates for wheat, soybean, corn, oil seeds, cotton, and vegetable all kept increasing until the 2010s (Figure 3).

Corn is the only mono-crop receiving N fertilizers at approximately 7 Tg N yr^{-1} in the 2010s (Figure 4 is the average of different scenarios; the different scenarios were showed in Figure S4&5). Among all the crop types, soybean received the least amount of N input which was about 0.1-0.2 Tg N yr^{-1}. The total N fertilizers used in soybean and oil seeds increased from the 1950s and then leveled off in the mid-1990s, and the N input for vegetable, mid-season rice, late rice, and wheat all kept

https://doi.org/10.5194/essd-2022-263
Preprint. Discussion started: 22 August 2022

increasing until the 2010s (Figure 4). In comparison, the N fertilizers-use in cotton and other crops leveled off in the 1990s, while the N input for early rice and late rice did not decline until the 1990s (Figure 4).



170 Figure 3. Nitrogen fertilizers use in major crop types from 1952 to 2018 (Unit: g N m^{-2} yr^{-1}).

https://doi.org/10.5194/essd-2022-263
Preprint. Discussion started: 22 August 2022

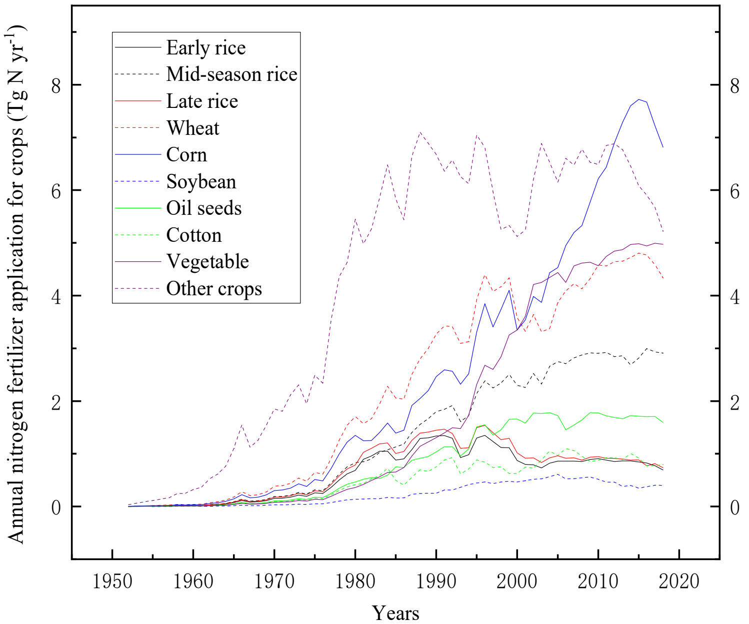


Figure 4. Total nitrogen fertilizer input in major crop types from 1952 to 2018 (Unit: Tg N yr^{-1}).

3.3 Spatial distribution of nitrogen fertilizers use in China

Our reconstructed maps show that the N fertilizers use in 1952 was generally lower than 1 g N m^{-2} yr^{-1} (Figure 5a), while the N fertilizers use increased to 4-8 g N m^{-2} yr^{-1} in 1980 and >16 g N m^{-2} yr^{-1} in 2000 in traditional agricultural plains including the Sichuan Plain and the Northern China Plain (Figure 5b). The higher N fertilizers use areas further expanded from 2000 to 2018 in the Northern China Plain, Northeast China Plain, and the northwest region (Figure 5d). In comparison, the uncertainties of the N fertilizers use rate were generally lower than 0.5 g N m^{-2} yr^{-1} in most of the area in China, but it kept increasing since 1952 to 2018 in northern, eastern, and northwestern regions (Figure 5g-h). Relatively higher uncertainties (> 4 g N m^{-2} yr^{-1}) were found in the Northern China Plain in 2018 (Figure 5h).

https://doi.org/10.5194/essd-2022-263
Preprint. Discussion started: 22 August 2022

Open Access Earth System Science Data Discussions

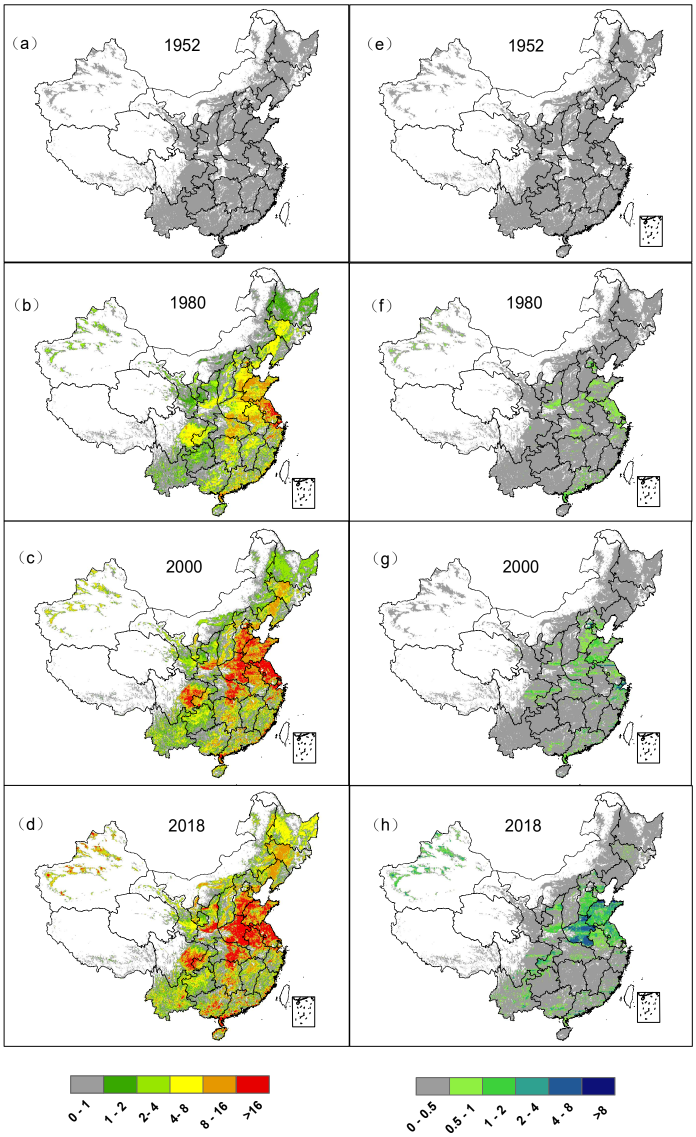


Figure 5. Spatial distribution of the rates (a-d) and the uncertainties (e-h) of nitrogen fertilizers use during different periods in China (the four panels from the top to the bottom indicate the rates (left) and the uncertainties (right) in 1952, 1980, 2000, and 2018, respectively; the value in the scale bar indicates the N fertilizers use rate per square meter of cropland).

https://doi.org/10.5194/essd-2022-263
Preprint. Discussion started: 22 August 2022

3.3 Comparison of newly reconstructed data and other data

We compared the reconstructed N fertilizers use rate maps with existing datasets. Specifically, the existing datasets describe N fertilizers use in two ways. The first one depicts N fertilizers use rate in per square meter cropland of each pixel. For example, our reconstructed data with the datasets published by Nishina et al. (2017) and Lu and Tian (2017) showed comparisons among the N fertilizers use in 1961, 1980, 1990, and 2013 (Figure 6), in which the Nishina et al. (2017)'s dataset on the N fertilizers use rate for the national average value (i.e. one value for each year) failed to capture the spatial heterogeneities. For the years 1961 and 1980, our reconstructed data on N fertilizers use rates were higher than the Nishina et al. (2017)'s dataset but slightly lower than the Lu and Tian (2017)'s dataset in the most areas of China (Figure 6a&b, 6e&f, 6i&j). For the year 1990, our reconstructed N fertilizer rates were generally higher than the other two datasets in the east of China (Figure 6c, 6g, 6k). The N fertilizers use was recorded only 15.3 g N m^{-2} yr^{-1} in 2010 in the Nishina et al. (2017)'s dataset, which was much lower than Lu and Tian (2017) and our study, which derived 20-35 g N m^{-2} yr^{-1} and >20 g N m^{-2} yr^{-1} respectively (Figure 6d, 6h, 6l). In addition, the N fertilizers use rates were lower in Lu and Tian (2017) than our reconstructed data in most of the northern and eastern provinces in 2013 (provinces dominated by red color in Figure 7l).

The second approach we used N fertilizers use rates by per square meter of land for a comparison between our reconstructed data and other two studies by Potter et al. (2010) and Houlton et al. (2019) (Figure 7). Overall, we found similar patterns between our reconstructed data and the Potter et al. (2010) and Houlton et al. (2019) datasets. Generally, both Potter et al. (2010) and Houlton et al. (2019) overestimated the China's cropland distribution in low-coverage areas, especially in the north and northwest regions (grey area in Figure 7c&d). Besides, N fertilizers use rates in our reconstructed data were higher than the Potter et al. (2010) during the period of 1994-2001 in traditionally cultivated plains (e.g. the Sichuan Plain, the Northern China Plain, and the Northeast China Plain) (Figure 7a&c). When compared with the Houlton et al. (2019)'s dataset, our reconstructed data showed the higher N fertilizers use in 2015 in the northwest region and the Northern China Plain, but lower N fertilizers use in the southwest region (Figure 7b&d).

https://doi.org/10.5194/essd-2022-263
Preprint. Discussion started: 22 August 2022

Open Access Earth System Science Data Discussions

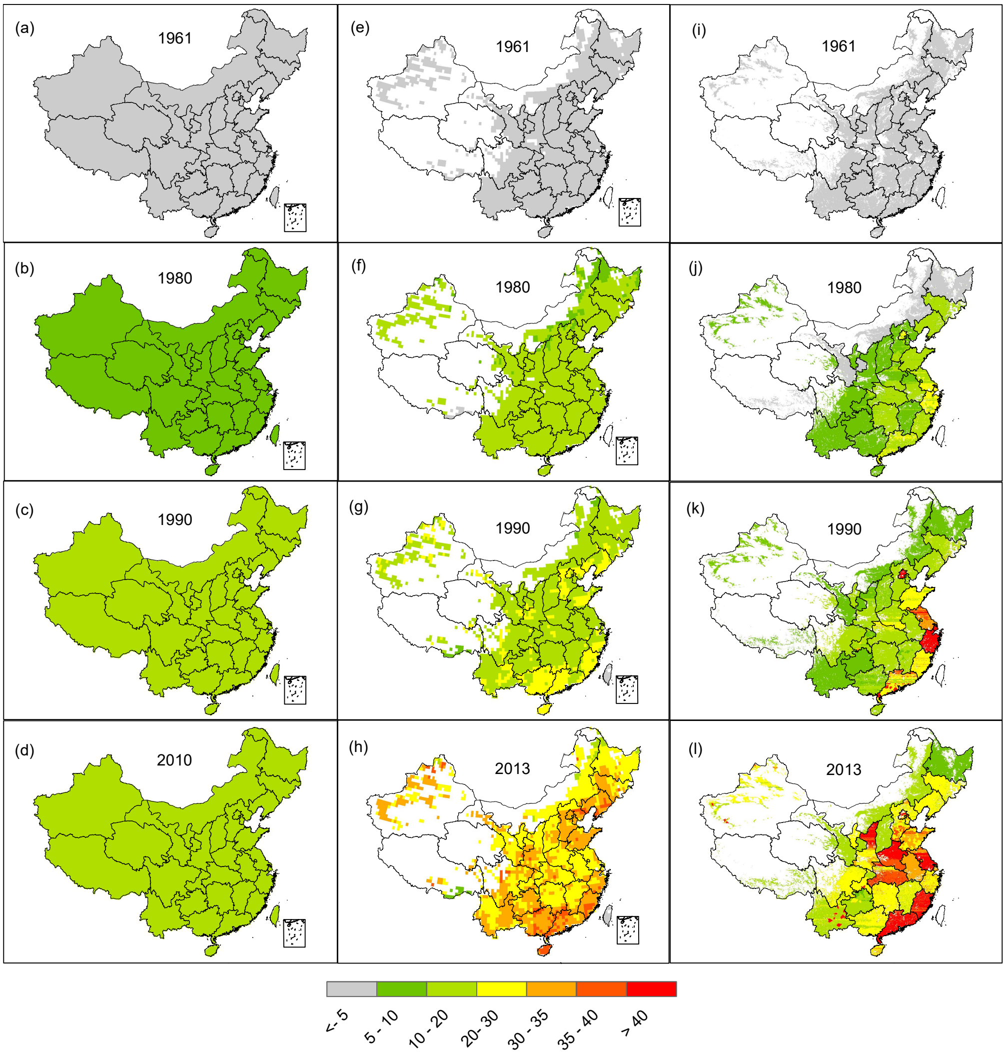


Figure 6. Distribution of nitrogen fertilizers use (a-c) in 1961, (d-f) in 1980, (g-i) in 1990, and (j-l) in 2013 (left column: Nishina et al. (2017)'s data; central column: Lu et al. (2017)'s data; right column: this study; the values indicate N fertilizers use rates per square meter cropland of each grid-cell).

https://doi.org/10.5194/essd-2022-263
Preprint. Discussion started: 22 August 2022

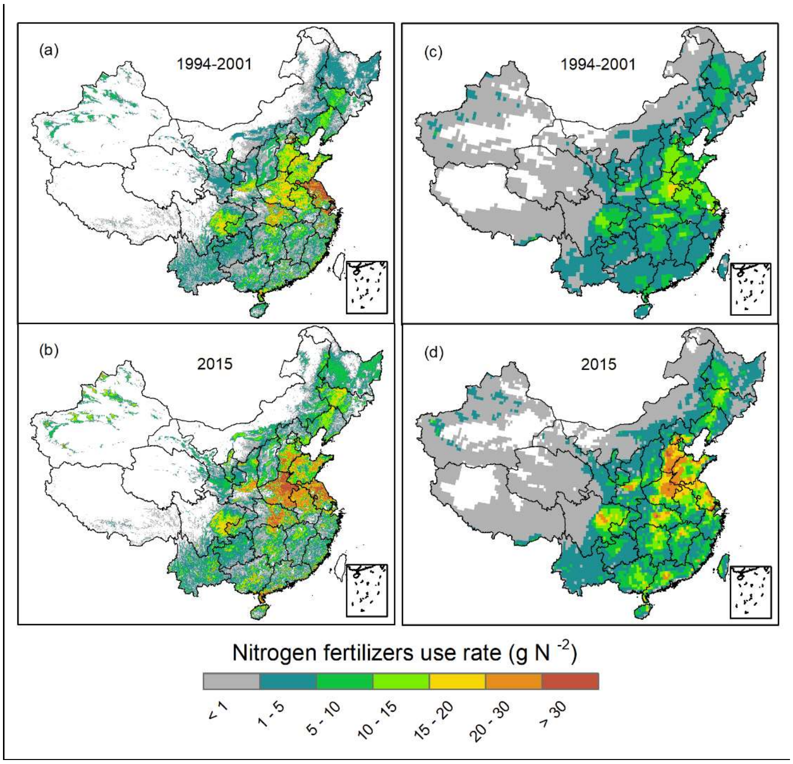


Figure 7. Distribution of nitrogen fertilizers use (a & c) in 1994-2001 and (b & d) in 2015 (panels a-b: this study: panel c: data from Potter et al. (2010); panel d: data from Houlton et al. (2019); the value indicates N fertilizers use rates per square meter of land).

4 Discussion and conclusion

4.1 Temporal changes in the nitrogen fertilizers use

The temporal changes of the N fertilizers use in China's cropland during the study period (1952-2018) are unprecedented. The total N fertilizers input has increased by approximately 52 times from 0.6 Tg N yr^{-1} in 1952 to the peak of 31.15 Tg N yr^{-1} in 2014. Together with population growth, the cropland expansion and the N management in crop fields contributed to this sharp increase of N fertilizers use in China's cropland over time. Our study found 39.3% (41.1 Mha) increase of the area of planted crops from the 1950s to the 2010s (data derived from Chinese Statistical Yearbook), and 98 folds increase of the N fertilizers use, which were 0.19 g N m^{-2} yr^{-1} in the 1950s to 18.38 g N m^{-2} yr^{-1} in the 2010s suggesting a marked transformation of the China's environment.

The tremendous amount of N input in the soil has greatly altered the biogeochemical cycles and endangered terrestrial and aquatic ecosystems in China (Guo et al., 2010; Domagalski et al., 2007; Yang, 2001; Liu et al., 2014). Former studies claimed that there is a climate benefit potential of the N fertilizers use on soil carbon storage enhancement (Tian et al., 2011; Melillo et al., 2010). Yet, such benefits could be completely counteracted or even exceeded by the boosted N_2O production (Zaehle et al., 2011; Liu and Greaver, 2009). Lately, China has made greater efforts to reduce the N fertilizers use in croplands. For instance, the Ministry of Agriculture of China's "One control, two minus, three basic" policy for the "Fertilizer Use Zero-Growth Action Plan by 2020" greatly limited or even reduced the fertilizers use (The Ministry of Agriculture of China, 2015). Our study clearly identified the effect of this policy, in which we found the total N fertilizers input decreased by 9.1% (2.84 Tg N yr^{-1}) from 2014 to 2018 (Figure 2). Our results also revealed the reduction in the national N fertilizers use in cropland since 2014 was due to the less planted crop area and the better N management in crop fields. In our study, the crop planted area in China was decreased by 2.3% (3.4 Mha) from 2015 to 2018 (http://www.stats.gov.cn/) which consequently helped reducing the N fertilizer input in cropland by 0.63 Tg N yr^{-1}. The better N management (i.e. improved N fertilizers use) in crop fields was the significant factor for the reduction of national N input as evidenced by 9.4% reductions in the N fertilizers use rates from 2014 to 2018 in China's cropland that we identified in our study (Figure 2).

The dynamics of N fertilizers present in China's cropland is complex due to the nature of different fertilizers, their use and management practices. The decrease of the N fertilizers input since 2014 in our study was caused by the reduction of N-only fertilizers, while the N of the compound fertilizers has been increasing from 1993 to 2018 (Figure 2). It has been reported that because of the varying energy consumptions during production and application processes, some N present in compound fertilizers may increase (Chen et al., 2020; McLaughlin, 2000; Gellings and Parmenter, 2004). Besides, fertilizers response differently to environmental factors and are therefore varied in emission potentials (Bouwman et al., 2002; Shcherbak et al., 2014). Thus, the shift of the use of N fertilizer types might potentially affect the N_2O emission in both during the producing processes and during the field application, implying that this shift in fertilizers use habit can impact on GHG budget of China, which should be examined.

4.2 Nitrogen fertilizers use by crop types

Surprisingly, we found that the most intensively fertilized crop was not grain crop but vegetable and other crops in China (Figure 3). Some surveys documented that fertilizers received by vegetables could be 3.3 times higher than grain crops suggesting that vegetable and other crop lands would play different roles in GHG emissions than the grain crop (Huang et al., 2017; Hou et al., 2017). In our study, the major component of the other crops was orchard, which accounted for 10% of the total planted area in China (according to the data obtained from http://www.stats.gov.cn/) and indicated higher rates of N fertilizers use. We found about 2-to-5-folds of the N fertilizers use rates in orchards in China than in grain crops (Table 2). In our study, we found the highest N fertilizers use (111.5-120.8 g N m^{-2} yr^{-1}) was in the apple orchard in the Loess Plateau (Table

https://doi.org/10.5194/essd-2022-263
Preprint. Discussion started: 22 August 2022

Open Access Earth System Science Data Discussions

2) suggesting that the orchards in dryland areas of China not only demand higher amount of water but also the increased use of N fertilizers. However, irrigation and higher N fertilizers use may together amplify the GHGs emissions as nitrification and denitrification processes might potentially be boosted (Trost et al., 2013). Given the large acreage of orchard and exponential rise of N_2O in response to N inputs increase (Bouwman et al., 2002; Shcherbak et al., 2014), it can be anticipated that the N_2O emission introduced by high N use in other crops might be an essential contributor to China's GHG budget. Many of the previous estimations have focused on GHG emissions from grain crops such as corn, rice, and wheat (Shcherbak et al., 2014; Ju et al., 2009; Huang and Tang, 2010), while our study implies that the GHGs emissions could be even larger from non-grain crops as the intensive N fertilizers use were identified in vegetable and other crops (Figure 3&4).

Despite we found the national average fertilizers use rates in grain crops (e.g. corn, rice and wheat) were reasonable, ranging from 12-20 g N m^{-2} yr^{-1} in the 2010s in China (Figure 3), the rates greatly varied among provinces. This clearly indicates the spatial non-uniformity in N fertilizers use in grain crops and location-specific implications for soils and environments in China. For example, N-only fertilizers use in corn was as low as 2.2-7.3 g N m^{-2} yr^{-1} in Northeast China Plain in 2018 known to be equipped with fertile soils (e.g. Jilin, Heilongjiang according to CSY data), while it was as high as 15.3-16.7 g N m^{-2} yr^{-1} in less fertile soils in the northwest region in 2018 (e.g., Shannxi and Gansu according to CSY data). This is consistent to previous study, which revealed that 20%-40% of the grain crops were over-fertilized in China using national survey data collected from 2002-2005 (Yan et al., 2017). Although over-use of N fertilizers in grain crops has been widely reported in China (Wu et al., 2018; Zhang et al., 2015; Ren et al., 2021), our study indicates that the over-use might be more intensive in producing of vegetables and fruits, particularly in drier regions where demand of water and fertilizers is high. Former study also suggested that the vegetables and fruits had 2.4-6.2 times higher N fertilizers demand in China (38.8-55.5 g N m^{-2} yr^{-1}) than in Europe and the U.S. (9.6-16.5 g N m^{-2} yr^{-1}), resulting into a much lower N fertilizers use efficiency in these crops (1/2-1/3 from that of the U.S.) (Wu et al., 2016). Since vegetables and orchard area accounts for 20% of the total planted area in China (CAY data in 2018), such high N fertilizers use rates together with the water use imply a large potential of economic and environmental benefits from optimizing fertilizers use in these non-grain crops.

Table 2 Nitrogen fertilizers use rates in minor crops reported in China.

Crop type	N fertilizers use (g N m^{-2} yr^{-1})	References
Barley	22.9	(Zaituniguli et al., 2021)
Sugarcane	36.0	(Zong, 2017)
Tobacco	51.8	(Hou et al., 2017)
Sugar crop	69.6	(Hou et al., 2017)
Apple (Loess Plateau)	111.5-120.8	(Chen et al., 2018)

https://doi.org/10.5194/essd-2022-263
Preprint. Discussion started: 22 August 2022

Apple (Shandong)	49.0	(Wei and Jiang, 2012)
Peach	55.0	(Gao, 2010)
Citrus	51.3	(Liang, 2007)
Grape (Northern China)	114.2	(Lu et al., 2012)
Pear	55.5 - 68.7	(Wu et al., 2016; Zhang et al., 2020)

4.3 Spatial trends of nitrogen fertilizers use

China, being a large country with varying geographic and climatic features, the N fertilizers use rates in crops are dependent largely on types of the crop and the location where the crops are grown. In addition, how the cropland is being managed also plays a greater role in N fertilizers use rates. Previous studies revealed that the optimal level of the N fertilizers use rates for crops were at around 15-20 g N m^{-2} yr^{-1} in China (Zhu and Chen, 2002; Ju et al., 2009, 2004). In our study, the N fertilizers use rates maps revealed some of the widespread, over-fertilized crop field regions in China (Figure 6l). Surprisingly, the most over-fertilized provinces, which majorly distributed in the central China and the southeast China, received more than two-folds N fertilizers use rates than the suggested optimal rates (Figure 6l).

The N fertilizers use rates have become an important driver directly determining the estimations of the crop productions and the GHG emissions accounting in different parts of the world (Tian et al., 2018). Hence, the reconstructed N fertilizers use data in our study is potentially useful to improve the accounting of the GHGs budget in China, especially the N_2O emissions. In a previous study, we found that the widely used, FAO-based global land use and land cover data (e.g. HYDE, LUH2) overestimated the cropland distribution in low coverage areas but underestimated the cropland percentage in high coverage areas (Yu et al., 2021). This might explain the differences in the N fertilizers use rates between our reconstructed data and other products such as Potter et al. (2010), which were being released previously. When we presented the FAO-based cropland maps (Figure 7c&d), on the N fertilizers use product of the Potter et al. (2010), with overestimated low-coverage croplands in China, the maps clearly reflected diluted, low N fertilizers use rates in more intensively cultivated plains. Recently, the International Modeling Community has initiated a global N_2O Model Intercomparison Project (NMIP) to quantify the N_2O gas emission from the land surface using ten state-of-the-art terrestrial biosphere models (Tian et al., 2018), where the HYDE cropland and HYDE-based N fertilizers use data were selected as the forcing data in simulation of underrated/overrated N_2O emissions in high/low cropland coverage areas (Lu and Tian, 2017; Tian et al., 2018; Wang et al., 2020a). We consider that our reconstructed N fertilizers use data will be vital for quantifying the N_2O gas emissions from China's croplands in future and substantially help mitigate global warming.

We would like to reiterate that the provincial N fertilizers use rates reported in the Cost-benefit Report of the National Agricultural Products (CBR) were the most important reference we adopted while reconstructing the N fertilizers use maps in

https://doi.org/10.5194/essd-2022-263
Preprint. Discussion started: 22 August 2022

Open Access Earth System Science Data Discussions

this study. Nonetheless, for each province, there were cases, where always a few crop types were thinly planted, but missed the reporting of the N fertilizers use rates. For those missing crop types reported in each province, we filled the gap by assuming the N fertilizers use rates close to the nearby province or equal to the national average (see the method section). However, the N fertilizers use rates might greatly differ from our assumptions because farmers' habits largely varied. Besides, the N fertilizers input contributed from compound fertilizers were not directly available, which also introduced uncertainty in the total N fertilizers applied for each crop. Thus, we could have improved the N fertilizers use maps if we had obtained more detailed surveying data. The distribution of the crop types which missed reporting at the sub-county levels and some years increased uncertainty of the reconstruction further. We derived the crop rotation information from national surveys of 2341 counties carried out in 1980, 1990, 2000, 2002, and 2011 (Liu et al., 2018), as these data were not sufficient, so that we assumed that the crop types planted between surveyed years were relatively stable and the information of the nearest year was used as substitution. Therefore, there might have been higher uncertainties in the N fertilizers use rates reconstruction in non-surveyed years. Despite such limitations, our reconstructed data, developed from improved gridded maps and crop-specific statistical information, are advantageous in depicting the N fertilizers use and estimating the GHG (N_2O emission) budgets in China's croplands.

5 Data Availability

The N fertilizers use maps reconstructed in this study are publicly available via https://doi.org/10.6084/m9.figshare.20402490.v1 (Yu, 2022).

Author contributions

ZY designed the work. JL collected data and performed data entry. ZY analysed the data and wrote the paper. GRK provided comments to improve the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgement

We greatly acknowledge data entry assistance from Yanli Dong. This work was supported by National Natural Science Foundation of China (No. 32001166), the Natural Science Foundation of Jiangsu Higher Education Institution of China (20KJB170013), and the Startup Foundation for Introducing Talent of NUIST (No. 2019r059).

https://doi.org/10.5194/essd-2022-263
Preprint. Discussion started: 22 August 2022

References

Bouwman, A. F., Boumans, L. J. M., and Batjes, N. H.: Modeling global annual N2O and NO emissions from fertilized fields, Global Biogeochem. Cycles, 16, https://doi.org/10.1029/2001gb001812, 2002.

Chen, C. X., Liu, Z. J., Chen, Z. J., Huo, B. Q., and Zhou, J. B.: Evaluation the situation of fertilization and soil fertility in new and old Apple orchards of Loess Plateau, Chinese J. Soil Sci., 49, 1144–1149, 2018.

Chen, Y., Zhang, X., Yang, X., Lv, Y., Wu, J., Lin, L., Zhang, Y., Wang, G., Xiao, Y., Zhu, X., Yu, X., and Peng, H.: Emergy evaluation and economic analysis of compound fertilizer production: A case study from China, J. Clean. Prod., 260, https://doi.org/10.1016/j.jclepro.2020.121095, 2020.

"One control, two minus, three basic" governance rural pollution: http://www.chinanews.com/gn/2015/03-20/7146411.shtml, last access: 20 March 2015.

Domagalski, J., Lin, C., Luo, Y., Kang, J., Wang, S., Brown, L. R., and Munn, M. D.: Eutrophication study at the Panjiakou-Daheiting Reservoir system, northern Hebei Province, People's Republic of China: Chlorophyll-a model and sources of phosphorus and nitrogen, Agric. Water Manag., 94, https://doi.org/10.1016/j.agwat.2007.08.002, 2007.

Erisman, J. W., Sutton, M. A., Galloway, J., Klimont, Z., and Winiwarter, W.: How a century of ammonia synthesis changed the world, Nat. Geosci., 1, https://doi.org/10.1038/ngeo325, 2008.

FAOSTAT database: http://faostat.fao.org., last access: 25 May 2022.

Galloway, J. N., Dentener, F. J., Capone, D. G., Boyer, E. W., Howarth, R. W., Seitzinger, S. P., Asner, G. P., Cleveland, C. C., Green, P. A., Holland, E. A., Karl, D. M., Michaels, A. F., Porter, J. H., Townsend, A. R., and Vörösmarty, C. J.: Nitrogen cycles: Past, present, and future, Biogeochemistry, 70, https://doi.org/10.1007/s10533-004-0370-0, 2004.

Gao, M.: Studies on Current Situation of Fertilization and Optimization of Fertilization Model of Peach or Chard at Mountainous Area in Mid-Shandong, Shandong Agricultural University, 2010.

Gellings, C. and Parmenter, K.: Energy efficiency in fertilizer production and use, Encycl. Life Support Syst., 2004.

Guo, J. H., Liu, X. J., Zhang, Y., Shen, J. L., Han, W. X., Zhang, W. F., Christie, P., Goulding, K. W. T., Vitousek, P. M., and Zhang, F. S.: Significant acidification in major chinese croplands, Science, 327, https://doi.org/10.1126/science.1182570, 2010.

Hou, M.-Y., Li, Z., Wang, Z.-W., Yang, D.-L., Wang, L.-L., Xiu, W.-M., and Zhao, J.-N.: Estimation of fertilizer usage from main crops in China, J. Agric. Resour. Environ., 34, 360, 2017.

Houlton, B. Z., Almaraz, M., Aneja, V., Austin, A. T., Bai, E., Cassman, K. G., Compton, J. E., Davidson, E. A., Erisman, J. W., Galloway, J. N., Gu, B., Yao, G., Martinelli, L. A., Scow, K., Schlesinger, W. H., Tomich, T. P., Wang, C., and Zhang, X.: A World of Cobenefits: Solving the Global Nitrogen Challenge, https://doi.org/10.1029/2019EF001222, 2019.

Huang, J., Hu, R., Cao, J., and Rozelle, S.: Training programs and in-the-field guidance to reduce China's overuse of fertilizer without hurting profitability, https://doi.org/10.2489/63.5.165a, 2008.

Huang, S., Tang, J., Li, C., Zhang, H., and Yuan, S.: Reducing potential of chemical fertilizers and scientific fertilization countermeasure in vegetable production in China, J. Plant Nutr. Fertil., 23, 1480–1493, 2017.

Huang, Y. and Tang, Y.: An estimate of greenhouse gas (N2O and CO2) mitigation potential under various scenarios of nitrogen use efficiency in Chinese croplands, Glob. Chang. Biol., 16, https://doi.org/10.1111/j.1365-2486.2010.02187.x, 2010.

Ju, X., Liu, X., Zhang, F., and Roelcke, M.: Nitrogen fertilization, soil nitrate accumulation, and policy recommendations in several agricultural regions of China, https://doi.org/10.1579/0044-7447-33.6.300, 2004.

Ju, X. T., Xing, G. X., Chen, X. P., Zhang, S. L., Zhang, L. J., Liu, X. J., Cui, Z. L., Yin, B., Christie, P., Zhu, Z. L., and Zhang, F. S.: Reducing environmental risk by improving N management in intensive Chinese agricultural systems, Proc. Natl. Acad. Sci. U. S. A., 106, https://doi.org/10.1073/pnas.0813417106, 2009.

Kahrl, F., Li, Y., Su, Y., Tennigkeit, T., Wilkes, A., and Xu, J.: Greenhouse gas emissions from nitrogen fertilizer use in China, Environ. Sci. Policy, 13, https://doi.org/10.1016/j.envsci.2010.07.006, 2010.

Liang, S.: Studies on NPK fertilization status and the potential of reducing application rate in major citrus planting regions of China, Huazhong Agricultural University, 2007.

Liu, J., Kuang, W., Zhang, Z., Xu, X., Qin, Y., Ning, J., Zhou, W., Zhang, S., Li, R., Yan, C., Wu, S., Shi, X., Jiang, N., Yu, D., Pan, X., and Chi, W.: Spatiotemporal characteristics, patterns, and causes of land-use changes in China since the late 1980s, J. Geogr. Sci., 24, 195–210, https://doi.org/10.1007/s11442-014-1082-6, 2014.

Liu, L. and Greaver, T. L.: A review of nitrogen enrichment effects on three biogenic GHGs: The CO 2 sink may be largely offset by stimulated N2O and CH 4 emission, https://doi.org/10.1111/j.1461-0248.2009.01351.x, 2009.

Liu, Z., Yang, P., Wu, W., and You, L.: Spatiotemporal changes of cropping structure in China during 1980–2011, J. Geogr. Sci., 28, 1659–1671, https://doi.org/10.1007/s11442-018-1535-4, 2018.

Lu, C. and Tian, H.: Global nitrogen and phosphorus fertilizer use for agriculture production in the past half century: Shifted hot spots and nutrient imbalance, Earth Syst. Sci. Data, 9, 181–192, https://doi.org/10.5194/essd-9-181-2017, 2017.

Lu, S., Yan, Z., Chen, Q., and Zhang, F.: Evaluation of conventional nitrogen and phosphorus fertilization and potential environmental risk in intensive orchards of north China, J. Plant Nutr., 35, 1509–1525, 2012.

McLaughlin, N. B.: Comparison of energy inputs for inorganic fertilizer and manure based corn production, Can. Biosyst. Eng. / Le Genie des Biosyst. au Canada, 42, 2000.

Melillo, J. M., Kicklighter, D. W., Tian, H., and Butler, S.: Fertilizing Change: Carbon-Nitrogen Interactions and Carbon Storage in Land Ecosystems, https://doi.org/10.1142/9781848166561_0003, 2010.

Myhre, G., Shindell, D., Breon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., and Zhang, H.: Anthropogenic and natural radiative forcing, in: Climate Change 2013 the Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, https://doi.org/10.1017/CBO9781107415324.018, 2013.

Naughton, B. J.: The Chinese economy: Transitions and growth, MIT press, 2006.

https://doi.org/10.5194/essd-2022-263
Preprint. Discussion started: 22 August 2022

Nishina, K., Ito, A., Hanasaki, N., and Hayashi, S.: Reconstruction of spatially detailed global map of NH4+ and NO3− application in synthetic nitrogen fertilizer, Earth Syst. Sci. Data, 9, https://doi.org/10.5194/essd-9-149-2017, 2017.

Potter, P., Ramankutty, N., Bennett, E. M., and Donner, S. D.: Characterizing the spatial patterns of global fertilizer application and manure production, Earth Interact., 14, https://doi.org/10.1175/2009EI288.1, 2010.

Ren, C., Jin, S., Wu, Y., Zhang, B., Kanter, D., Wu, B., Xi, X., Zhang, X., Chen, D., Xu, J., and Gu, B.: Fertilizer overuse in Chinese smallholders due to lack of fixed inputs, J. Environ. Manage., 293, https://doi.org/10.1016/j.jenvman.2021.112913, 2021.

Shang, Z., Zhou, F., Smith, P., Saikawa, E., Ciais, P., Chang, J., Tian, H., Del Grosso, S. J., Ito, A., Chen, M., Wang, Q., Bo, Y., Cui, X., Castaldi, S., Juszczak, R., Kasimir, Å., Magliulo, V., Medinets, S., Medinets, V., Rees, R. M., Wohlfahrt, G., and Sabbatini, S.: Weakened growth of cropland-N2O emissions in China associated with nationwide policy interventions, Glob. Chang. Biol., 25, https://doi.org/10.1111/gcb.14741, 2019.

Shcherbak, I., Millar, N., and Robertson, G. P.: Global metaanalysis of the nonlinear response of soil nitrous oxide (N 2O) emissions to fertilizer nitrogen, Proc. Natl. Acad. Sci. U. S. A., 111, 9199–9204, https://doi.org/10.1073/pnas.1322434111, 2014.

Strokal, M., Ma, L., Bai, Z., Luan, S., Kroeze, C., Oenema, O., Velthof, G., and Zhang, F.: Alarming nutrient pollution of Chinese rivers as a result of agricultural transitions, Environ. Res. Lett., 11, https://doi.org/10.1088/1748-9326/11/2/024014, 2016.

Sutton, M. A. and Bleeker, A.: Environmental science: The shape of nitrogen to come, https://doi.org/10.1038/nature11954, 2013.

Tian, H., Melillo, J., Lu, C., Kicklighter, D., Liu, M., Ren, W., Xu, X., Chen, G., Zhang, C., Pan, S., Liu, J., and Running, S.: China's terrestrial carbon balance: Contributions from multiple global change factors, Global Biogeochem. Cycles, 25, https://doi.org/10.1029/2010GB003838, 2011.

Tian, H., Lu, C., Melillo, J., Ren, W., Huang, Y., Xu, X., Liu, M., Zhang, C., Chen, G., Pan, S., Liu, J., and Reilly, J.: Food benefit and climate warming potential of nitrogen fertilizer uses in China, Environ. Res. Lett., 7, https://doi.org/10.1088/1748-9326/7/4/044020, 2012.

Tian, H., Yang, J., Lu, C., Xu, R., Canadell, J. G., Jackson, R. B., Arneth, A., Chang, J., Chen, G., Ciais, P., Gerber, S., Ito, A., Huang, Y., Joos, F., Lienert, S., Messina, P., Olin, S., Pan, S., Peng, C., Saikawa, E., Thompson, R. L., Vuichard, N., Winiwarter, W., Zaehle, S., Zhang, B., Zhang, K., and Zhu, Q.: The global N2O model intercomparison project, Bull. Am. Meteorol. Soc., 99, 1231–1251, https://doi.org/10.1175/BAMS-D-17-0212.1, 2018.

Trost, B., Prochnow, A., Drastig, K., Meyer-Aurich, A., Ellmer, F., and Baumecker, M.: Irrigation, soil organic carbon and N2O emissions. A review, https://doi.org/10.1007/s13593-013-0134-0, 2013.

Wang, Q., Zhou, F., Shang, Z., Ciais, P., Winiwarter, W., Jackson, R. B., Tubiello, F. N., Janssens-Maenhout, G., Tian, H., Cui, X., Canadell, J. G., Piao, S., and Tao, S.: Data-driven estimates of global nitrous oxide emissions from croplands, Natl. Sci. Rev., 7, 441–452, https://doi.org/10.1093/nsr/nwz087, 2020a.

Wang, S., Zhang, X., Wang, C., Zhang, X., Reis, S., Xu, J., and Gu, B.: A high-resolution map of reactive nitrogen inputs to China, Sci. Data, 7, https://doi.org/10.1038/s41597-020-00718-5, 2020b.

Wei, S. and Jiang, Y.: Investigation on Fertilization Status in Apple Orchards of Shandong Province, Shandong Agric. Sci., 44, 77–79, 2012.

Wu, L., Zhang, W., Chen, X., Gui, Z., Fan, M., Chen, Q., and Zhang, F.: Nitrogen fertilizer input and nitrogen use efficiency in Chinese farmland, Soil Fertil. Sci. China, 4, 76–83, 2016.

Wu, Y., Xi, X., Tang, X., Luo, D., Gu, B., Lam, S. K., Vitousek, P. M., and Chen, D.: Policy distortions, farm size, and the overuse of agricultural chemicals in China, Proc. Natl. Acad. Sci. U. S. A., 115, 2018.

Yan, X., Jin, J. Y., and Liang, M. Z.: Fertilizer use efficiencies and yield-increasing rates of grain crops in China, 49, 1067–1077, 2017.

Yang, J. Q.: Measures for pollution remedy and ecological protection in Dianchi Lake, Journal Hydraul. Eng., 2001.

Yu, Z. and Lu, C.: Historical cropland expansion and abandonment in the continental U.S. during 1850 to 2016, Glob. Ecol. Biogeogr., 27, 322–333, https://doi.org/10.1111/geb.12697, 2018.

Yu, Z., Lu, C., Tian, H., and Canadell, J. G.: Largely underestimated carbon emission from land use and land cover change in the conterminous US, Glob. Chang. Biol., gcb.14768, https://doi.org/10.1111/gcb.14768, 2019.

Yu, Z., Jin, X., Miao, L., and Yang, X.: A historical reconstruction of cropland in China from 1900 to 2016, Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2020-382, 2021.

Zaehle, S., Ciais, P., Friend, A. D., and Prieur, V.: Carbon benefits of anthropogenic reactive nitrogen offset by nitrous oxide emissions, Nat. Geosci., 4, https://doi.org/10.1038/ngeo1207, 2011.

Zaituniguli, K., Tuerxun, T., Tu, Z., and Aikebaier, Y.: Effects of Different Fertilizers on Photosynthetic Characteristics and Yield of Sorghum Leaves in Arid Areas, Acta Agric. Boreali-Sinica, 36, 127–134, 2021.

Zhang, L., Zhang, H., and He, X.: Investigation and analysis on nutrient status of soil and leaves in pear orchards of Chongqing, Soil Fertil. Sci. China, 2, 107–115, 2020.

Zhang, S., Gao, P., Tong, Y., Norse, D., Lu, Y., and Powlson, D.: Overcoming nitrogen fertilizer over-use through technical and advisory approaches: A case study from Shaanxi Province, northwest China, Agric. Ecosyst. Environ., 209, https://doi.org/10.1016/j.agee.2015.03.002, 2015.

Zhou, F., Shang, Z., Ciais, P., Tao, S., Piao, S., Raymond, P., He, C., Li, B., Wang, R., Wang, X., Peng, S., Zeng, Z., Chen, H., Ying, N., Hou, X., and Xu, P.: A new high-resolution N2O emission inventory for China in 2008, Environ. Sci. Technol., 48, https://doi.org/10.1021/es5018027, 2014.

Zhu, Z. L. and Chen, D. L.: Nitrogen fertilizer use in China - Contributions to food production, impacts on the environment and best management strategies, Nutr. Cycl. Agroecosystems, 63, https://doi.org/10.1023/A:1021107026067, 2002.

Zong, H.: Studies and comparisons of the Nitrogen fertilizer use efficiency in sugercane industry in China and Autralia, World Agric., 453, 185–193, 2017.