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Global manure nitrogen production and application in cropland during 1860–2014: a 5 arcmin gridded global dataset for Earth system modeling

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Abstract. Given the important role of nitrogen input from livestock systems in terrestrial nutrient cycles and the atmospheric chemical composition, it is vital to have a robust estimation of the magnitude and spatiotemporal variation in manure nitrogen production and its application to cropland across the globe. In this study, we used the dataset from the Global Livestock Impact Mapping System (GLIMS) in conjunction with country-specific annual livestock populations to reconstruct the manure nitrogen production during 1860–2014. The estimated manure nitrogen production increased from 21.4 $\mathrm{Tg\,N\,yr^{-1}}$ in 1860 to 131.0 $\mathrm{Tg\,N\,yr^{-1}}$ in 2014 with a significant annual increasing trend (0.7 $\mathrm{Tg\,N\,yr^{-1}}$, $p < 0.01$). Changes in manure nitrogen production exhibited high spatial variability and concentrated in several hotspots (e.g., Western Europe, India, northeastern China, and southeastern Australia) across the globe over the study period. In the 1860s, the northern midlatitude region was the largest manure producer, accounting for $\sim 52\,\%$ of the global total, while low-latitude regions became the largest share ($\sim 48\,\%$) in the most recent 5 years (2010–2014). Among all the continents, Asia accounted for over one-fourth of the global manure production during 1860–2014. Cattle dominated the manure nitrogen production and contributed $\sim 44\,\%$ of the total manure nitrogen production in 2014, followed by goats, sheep, swine, and chickens. The manure nitrogen application to cropland accounts for less than one-fifth of the total manure nitrogen production over the study period. The 5 arcmin gridded global dataset of manure nitrogen production generated from this study could be used as an input for global or regional land surface and ecosystem models to evaluate the impacts of manure nitrogen on key biogeochemical processes and water quality. To ensure food security and environmental sustainability, it is necessary to implement proper manure management practices on cropland across the globe. Datasets are available at https://doi.org/10.1594/PANGAEA.871980 (Zhang et al., 2017).

1 Introduction

Human-induced nitrogen flow, mainly driven by the increasing needs for food production, has a tremendous impact on the Earth's biogeochemical cycles (Bouwman et al., 2013; Galloway et al., 2008; Liu et al., 2010). Chemical fertilizer use began to play an important role in enhancing crop yield in the 1960s (Lu and Tian, 2017; Potter et al., 2010), and manure has long been recognized as a traditional source of soil nutrients for centuries, contributing up to ~ 37–61 % of the total nitrogen input to the land surface (Bouwman et al., 2013). Manure nitrogen production is expected to increase in the coming decades due to the growing demand for livestock populations as a result of the ever-increasing human population and shifts in diet structure with more meat consumption (Herrero and Thornton, 2013). The resultant changes have been suggested to surpass the sustainability threshold (Pelletier and Tyedmers, 2010) with a substantial impact on biogeochemical processes and greenhouse gas balance in terrestrial ecosystems (Tian et al., 2016).

The increasing application of manure nutrients has contributed to an increase in crop production and, at the same time, has been identified as one of the major causes for a litany of environmental problems that impinge on the land, the aquatic ecosystem, and even the atmospheric composition (Bouwman et al., 2013; Burkart and James, 1999; Davidson and Kanter, 2014; Potter et al., 2010). To maintain high yield, farmers tend to apply large amounts of nitrogen fertilizer and organic manure, especially in intensive crop-producing systems. A recent study revealed that only 38 % of total reactive nitrogen input was finally transferred into harvested crop yield (Liu et al., 2016). Part of the surplus nitrogen can be accumulated in soil nitrogen pools. Manure-derived nitrous oxide (N_2O) accounts for 44 % of total anthropogenic N_2O emissions, which is the largest anthropogenic stratospheric ozone-depleting substance and the third most important anthropogenic greenhouse gas (Davidson, 2009; Davidson and Kanter, 2014; Tian et al., 2016). It has been suggested that manure was the single largest source of the anthropogenic emission of N_2O in the 2000s (Davidson, 2009; Davidson and Kanter, 2014; Syakila and Kroeze, 2011). At the same time, manure also acted as the dominant source of ammonia (NH_3), which played a vital role in the formation of atmospheric particulate matter (PM), such as $PM_{2.5}$, and atmospheric nitrogen deposition (Behera et al., 2013; Sutton et al., 2013). Manure production contributed over 66 % of NH_3 emissions from the agricultural system (Beusen et al., 2008). Thus, increasing manure production could lead to an increase in NH_3 emissions, which impairs public and environmental health (Sutton et al., 2013). The rest of the surplus nitrogen can leach through the soil profile and contaminate groundwater in the form of nitrate (Ju et al., 2006). Excess nitrogen together with phosphorous can stimulate the eutrophication of inland water (Conley et al., 2009), be transported far away from original sources, exacerbate degrading coastal water quality, and even lead to hypoxia (Burkart and James, 1999; Yang et al., 2015).

To determine the status of unevenly distributed nitrogen at large scales, it is critical to have a good understanding of the geographic distribution of nitrogen inputs from different sectors. In spite of extensive studies on the development of nitrogen fertilizer data at both regional and global scales (FAOSTAT, 2014; Lu and Tian, 2017; Matthews, 1994; Nishina et al., 2017; Potter et al., 2010), most previous datasets for manure nitrogen production at the global scale either relied on a livestock population dataset with coarse resolution or were only available for limited time periods without consecutive inter-annual variation; e.g., Herrero and Thornton (2013), Holland et al. (2005), Liu et al. (2010), and Potter et al. (2010). Recent research has expanded the estimation of manure nutrient production in the conterminous United States during 1930–2012 and in China during 2002–2008 (Ouyang et al., 2013; Yang et al., 2016). In the conterminous United States, manure nitrogen has increased by 46 % from 1930 to 2012 with substantial spatial heterogeneity (Yang et al., 2016). In China, manure nutrients are unevenly distributed with seven provinces contributing over half of the total manure nitrogen (Ouyang et al., 2013).

Although these datasets have expanded our recognition of manure nitrogen estimates, spatially explicit estimates of manure nitrogen production on a global scale are still lacking. To reduce the uncertainty in estimating several key biogeochemical processes at the global scale, such as the continuously increased emission of nitrous oxide and the occurrences of inland and coastal hypoxia due to nutrient enrichment at large scales, it is necessary to quantify the spatial and temporal variations in manure nitrogen production over a long period. Together with other data, quantification of manure nitrogen production could also be used to generate a comprehensive assessment for livestock sectors and design sustainable options for the sector's development (Herrero and Thornton, 2013). At the same time, it could quantify the uncertainties in analyzing the key nutrient cycles in terrestrial ecosystems and their feedback to the climate over a century-long period.

The original Gridded Livestock of the World (GLW) database (Wint and Robinson, 2007) was further revised and improved through the collection of more up-to-date livestock statistics and the application of finer-resolution predictor variables and more reasonable analytical procedures to develop the Global Livestock Impact Mapping System (GLIMS, also called GLW2; Robinson et al., 2014). GLIMS offers an exceptional opportunity to improve manure data from earlier studies and extend our knowledge of manure production over a century-long period (Robinson et al., 2014). Thus, the major objective of this study is to produce global gridded maps of manure nitrogen production at a 5 arcmin resolution in latitude by longitude during 1860–2014. More specifically, we (1) estimate the magnitude and spatial and temporal variation in manure nitrogen production, (2) quantify the relative contribution of major livestock groups on the manure nitrogen production, (3) investigate the spatial and temporal variation in manure nitrogen applied to cropland, and (4) discuss the impacts of manure nitrogen production on terrestrial biogeochemical cycles.

2 Methods

2.1 Manure nitrogen production

To develop the gridded annual nitrogen production rate from manure during 1860–2014, we used the dataset from GLIMS (GLW2), which provided the spatial distribution of different livestock at a spatial resolution of 0.00833° (a nominal pixel resolution of approximately 1 × 1 km at the Equator) for cattle (dairy and other cattle), swine,

Table 1. Summary of data sources used in this study.

Data source	Dataset	Units	Reference
Global Livestock Impact Mapping System (GLIMS)	Spatial distribution of different livestock	Head	Robinson et al. (2014)
FAOSTAT 2014	Annual stock of country-specific livestock	Head	FAOSTAT (2014)
History Database of the Global Environment (HYDE)	Fills the gaps for years without livestock populations from FAOSTAT	n/a	Mitchell (1998a, b, 1993)
IPCC 2006 guidelines	Regional excretion rate from livestock	$\mathrm{kg\,N\,animal^{-1}\,yr^{-1}}$	IPCC (2006)
IPCC 2006 guidelines	Typical animal mass from livestock	$\mathrm{kg\,animal^{-1}}$	IPCC (2006)
Holland et al., 2005	Manure nitrogen production from 1860 to 1960	$\mathrm{Tg\,N\,yr^{-1}}$	Holland et al. (2005)
Livestock production systems	Manure management for different livestock production systems	n/a	Herrero et al. (2013)
History Database of the Global Environment (HYDE 3.2)	Global cropland distributions from 1860 to 2014	n/a	Klein Goldewijk et al. (2016)
Siebert et al., 2013	Spatial distribution of global irrigated area (expressed as the percentage of area equipped for irrigation)	n/a	Siebert et al. (2013)
FAOSTAT 2014	Country-level area equipped for irrigation	$\mathrm{km^2}$	FAOSTAT (2014)

chickens, goats, sheep, and ducks with a partial distribution (https://livestock.geo-wiki.org/home-2/; Robinson et al., 2014). The annual variation in national livestock stock from 1961 to 2014 was obtained from FAOSTAT (FAOSTAT, 2014; http://faostat.fao.org/site/291/default.aspx). For the countries (including the United States, Australia, Brazil, Canada, China, and Mongolia) with subregional (province- or state-level) cattle populations, we disaggregated FAO country-level populations into subregions (see detailed description in Dangal et al., 2017). For the missing data in FAOSTAT, the annual trend was generated by linear interpolation of the five time periods (1960, 1970, 1980, 1990, and 1998) of livestock populations from the History Database of the Global Environment (HYDE; Table S1 in the Supplement) to fill the gaps (Mitchell, 1998a, b, 1993). Default values for the regional nitrogen excretion rates of different livestock were obtained from the Intergovernmental Panel on Climate Change (IPCC) 2006 guidelines (Tier 1; IPCC, 2006; Table S2). By using the livestock population (including cattle, swine, sheep, and poultry) from FAO Production Yearbooks, Holland et al. (2005) applied the default excretion rate suggested by Souchu and Etchanchu (1989) to generate the annual manure nitrogen production from 1860 to 1960. We obtained the change in manure nitrogen production before 1960 from Holland et al. (2005) and applied it to each grid cell to estimate the amount of manure nitrogen production from 1860 to 1960.

The development of the time series on the nitrogen excretion rate from livestock is provided below in more detail (Table 1). To distribute the yearly country-level livestock population from FAOSTAT (after 1960) or Holland et al. (before 1960), we standardized the livestock distribution with spatially explicit gridded information from GLIMS to match the annual country-level livestock records from FAOSTAT:

$$D(\mathrm{FAO})_{i,j,k} = D(\mathrm{GLIMS})_{i,j} \times \frac{\mathrm{NTH}(\mathrm{FAO})_{i,j,k}}{\mathrm{NTH}(\mathrm{GLIMS})_{i,j}}, \tag{1}$$

where NTH indicates the national total head of animal j from a specific country i (unit: head) in year k (k indicates 1961–2014). D indicates the density of animal j from a specific country i (unit: $\mathrm{head\,km^{-2}}$ land in each grid) in year k.

Then we calculated the average nitrogen excretion rate by applying the IPCC 2006 guidelines (Tier 1; IPCC, 2006):

$$N_{\mathrm{ex}_{(i,j)}} = N_{\mathrm{rate}_{(i,j)}} \times \frac{\mathrm{TAM}_{(i,j)}}{1000} \times 365, \tag{2}$$

where $N_{\mathrm{ex}_{(i,j)}}$ indicates annual N excretion for livestock category j from a specific country i (unit: $\mathrm{kg\,N\,animal^{-1}\,yr^{-1}}$), $N_{\mathrm{rate}_{(i,j)}}$ indicates the default N excretion rate for livestock category j from a specific country i (unit: kg N (1000 kg animal mass)$^{-1}$ day^{-1}), and $\mathrm{TAM}_{(i,j)}$ indicates typical animal mass for livestock category j from a specific region i (unit: $\mathrm{kg\,animal^{-1}}$). For cattle, we collected information for $N_{\mathrm{rate}_{(i,j)}}$ and $\mathrm{TAM}_{(i,j)}$ (Table S2.1) at the continent, country, and subregional level. For other livestock, we use region-specific values from IPCC (2006; Tables S2.2–2.3).

We calculated the gridded average nitrogen excretion rate with

$$N_{\mathrm{man}_{(i,j,k)}} = N_{\mathrm{ex}_{(i,j)}} \times D(\mathrm{FAO})_{(i,j,k)}, \tag{3}$$

where $N_{\mathrm{man}_{(i,j,k)}}$ indicates gridded average nitrogen excretion rates for livestock category j from a specific country i in year k (unit: $\mathrm{kg\,N\,km^{-2}\,yr^{-1}}$).

2.2 Manure nitrogen applied to cropland

We further developed the gridded map of the manure nitrogen applied to cropland at 5 arcmin of resolution based on

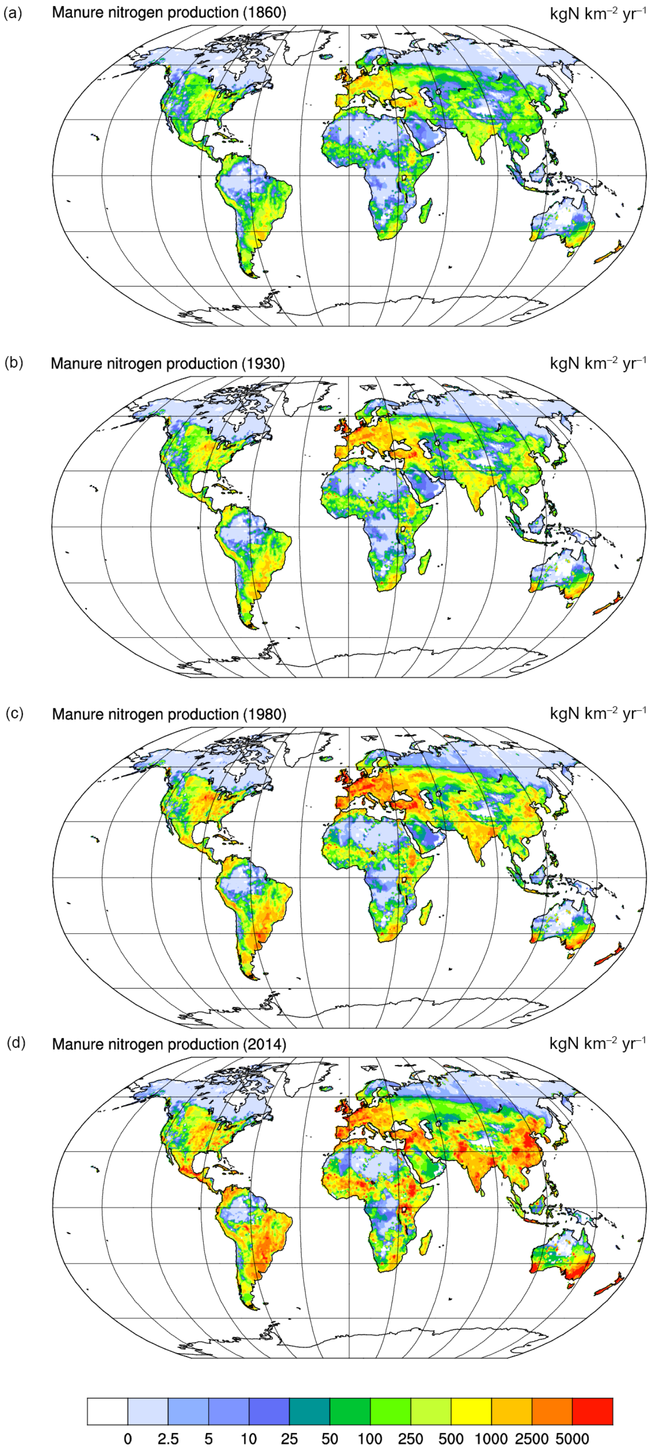

Figure 1. Spatial distribution of manure nitrogen production across the global land surface in the four years 1860, 1930, 1980, and 2014.

manure management in three livestock production systems, including rangeland-based systems, mixed rainfed farming systems, and mixed irrigated farming systems for cattle (dairy and other cattle), goats and sheep, and smallholder and industrial systems for poultry and swine (Herrero et al., 2013). Herrero et al. (2013) further classified the livestock systems into different agroecological zones (arid and semi-arid, humid and subhumid, and temperate and tropical highland areas) based on temperature and the length of the growing period (LGP). The data on the spatial distribution for livestock production systems for ruminants, swine, and chickens were obtained from GLIMS (https://livestock.geo-wiki.org/download/), which represents the status around 2006. Thus,

$$F_{\mathrm{M}(j,\,\mathrm{ProSys})} = F_{\mathrm{MT}(j,\mathrm{ProSys})} \cdot \left(1 - F_{\mathrm{MO}(j,\mathrm{ProSys})}\right) \cdot \left(1 - F_{\mathrm{Loss}(j,\mathrm{ProSys})}\right), \qquad (4)$$

where $F_{\mathrm{M}(j,\mathrm{ProSys})}$ indicates the fraction of manure from livestock category j applied to cropland, and $F_{\mathrm{MT}(j,\mathrm{ProSys})}$ indicates the fraction of total manure managed for different livestock production systems. $F_{\mathrm{MO}(j,\mathrm{ProSys})}$ indicates the fraction of managed manure to other use, e.g., the production of biogas. $F_{\mathrm{Loss}(j,\mathrm{ProSys})}$ indicates the fraction of managed manure lost through volatilization as $\mathrm{NH_3}$ and NO_x. All the parameters used in Eq. (4) can be found in Table S3. ProSys indicated livestock production systems for cattle (dairy and other cattle) and small ruminants, including rangeland-based systems (LGY: livestock-only systems in hyperarid areas; LGA: livestock-only systems in arid areas; LGH: livestock-only systems in humid areas; and LGT: livestock-only systems in temperate areas or tropical highlands), mixed rainfed farming systems (MRY: mixed rainfed systems in hyperarid areas; MRA: mixed rainfed systems in arid areas; MRH: mixed rainfed systems in humid areas; and MRT: mixed rainfed systems in temperate areas or tropical highlands) and mixed irrigated farming systems (MIY: mixed irrigated systems in hyperarid areas; MIA: mixed irrigated systems in arid areas; MIH: mixed irrigated systems in humid areas; and MIT: mixed irrigated systems in temperate areas or tropical highlands), and smallholder (POsm) and industrial (POin) for poultry and swine.

To develop the spatial maps for manure nitrogen applied to soils on cropland during 1860–2014, we made several assumptions due to absence of the appropriate data and calculated as

$$N_{\mathrm{man}_{\mathrm{CR}(j,k)}} = N_{\mathrm{man}_{(i,j,k)}} \times \begin{cases} F_{\mathrm{M}(j,\mathrm{ProSys_{rl}})} & \text{(5a)} \\ F_{\mathrm{M}(j,\mathrm{ProSys_{rd}})} \times \dfrac{f_{\mathrm{crp}(k)}}{f_{\mathrm{crp}(2006)}} + F_{\mathrm{M}(j,\mathrm{ProSys_{rl}})} \times \left(1 - \dfrac{f_{\mathrm{crp}(k)}}{f_{\mathrm{crp}(2006)}}\right) & \text{(5b)} \\ F_{\mathrm{M}(j,\mathrm{ProSys_{irri}})} \times \dfrac{f_{\mathrm{irri}(k)}}{f_{\mathrm{irri}(2006)}} + \left\{F_{\mathrm{M}(j,\mathrm{ProSys_{rd}})} \times \dfrac{f_{\mathrm{crp}(k)}}{f_{\mathrm{crp}(2006)}} + F_{\mathrm{M}(j,\mathrm{ProSys_{rl}})} \times \left(1 - \dfrac{f_{\mathrm{crp}(k)}}{f_{\mathrm{crp}(2006)}}\right)\right\} \times \left(1 - \dfrac{f_{\mathrm{irri}(k)}}{f_{\mathrm{irri}(2006)}}\right), & \text{(5c)} \end{cases}$$

where $N_{\mathrm{man}_{\mathrm{CR}(j,k)}}$ indicates the manure nitrogen applied to soils on cropland, and $F_{\mathrm{M}(j,\mathrm{ProSys_{rd}})}$ indicates the fraction of

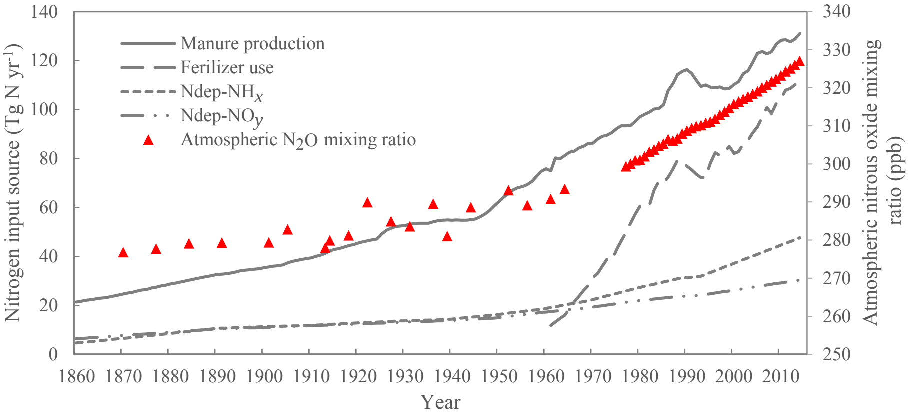

Figure 2. Comparison of nitrogen input from global manure production, fertilizer use, and atmospheric nitrogen deposition with atmospheric nitrous oxide mixing ratio during 1860–2014.

manure applied to mixed rainfed farming systems, including MRY, MRA, MRH, and MRT. $F_{\mathrm{M}(j,\mathrm{ProSys}_{\mathrm{irri}})}$ indicates the fraction of manure applied to mixed irrigated farming systems, including MIY, MIA, MIH, and MIT. $F_{\mathrm{M}(j,\mathrm{ProSys}_{\mathrm{rl}})}$ indicates the fraction of manure applied to rangeland-based systems, $f_{\mathrm{irri}(k)}$ indicates the fraction of irrigated area to the total area in year k in each grid cell, and $f_{\mathrm{crp}(k)}$ indicates the fraction of cropland area to the total area in year k in each grid cell.

The spatial distribution of livestock production systems in 2006 serves as a baseline map to characterize the change in livestock production system during 1860–2005. We also assumed that the spatial distribution of livestock production systems remained the same during 2006–2014. We assumed the following: if the grid cell was identified as a rangeland-based system, the livestock production system remained the same during the study period (See Eq. 5a); if the grid cell was identified as a mixed rainfed farming system, the percent change in the livestock production system would be proportional to the changes in the cropland area in that grid cell before 2006, and the mixed rainfed farming system was converted from a rangeland-based system (See Eq. 5b); if the grid cell was identified as a mixed irrigated farming system, the percent change in the livestock production system would be proportional to the changes in the irrigated area in that grid cell before 2006, and the mixed irrigated farming systems were converted from mixed rainfed farming systems (See Eq. 5c).

The gridded cropland distribution map during 1860–2014 was obtained from HYDE 3.2 (Klein Goldewijk et al., 2016). We spatialized the country-level area equipped for irrigation from FAOSTAT during 1961–2014 by adopting the gridded irrigated area (expressed as the percentage of area equipped for irrigation; Siebert et al., 2013) to create the gridded irrigation map during 1961–2014. We assumed the irrigated area did not change before 1961.

We assumed that if the grid cell was identified as smallholder for poultry and swine, the livestock production system remained the same during the study period; if the grid cell was identified as industrial, the fraction of the industrial livestock production system was assumed to be 0 in 1860 and 1 in 2006, and it linearly increased from 1860 to 2006 for swine and chickens.

Previous studies suggested that the intensive duck production system first came out in the early 1950s (Ahuja, 2013; Raud and Faure, 1994). Thus, the intensive duck production system was assumed to be 0 in 1950 and 81.6 % in 2008, and it linearly increased from 1950 to 2008. The rest was occupied by extensive duck production systems (Ahuja, 2013; Duc and Long, 2008; MOA, 2013; Raud and Faure, 1994).

3 Results

3.1 Temporal changes in manure nitrogen production

In this study, we quantified the total manure nitrogen production from six livestock categories, including cattle (dairy and other cattle), chickens, ducks, goats, swine, and sheep at a global scale during 1860–2014 (Fig. 1). We referred to the total mass of nitrogen excreted by livestock for the manure nitrogen production. The estimated global manure nitrogen production increased about 5 times from 21.4 Tg N yr^{-1} in 1860 to 131.0 Tg N yr^{-1} in 2014 with an overall significant increasing trend during 1860–2014 (0.7 Tg N yr^{-2}, $p < 0.01$; Fig. 2). In 1990, there was near peak manure production ($\sim$ 116.3 Tg N yr^{-1}) followed by a decrease until 1998 (108.4 Tg N yr^{-1}) and then an increase afterward.

3.2 Spatial patterns of manure nitrogen production

Manure nitrogen production exhibited large spatial variation over the study period. In the 1860s, the northern midlatitudes (NM, 30–60° N) accounted for over half of the

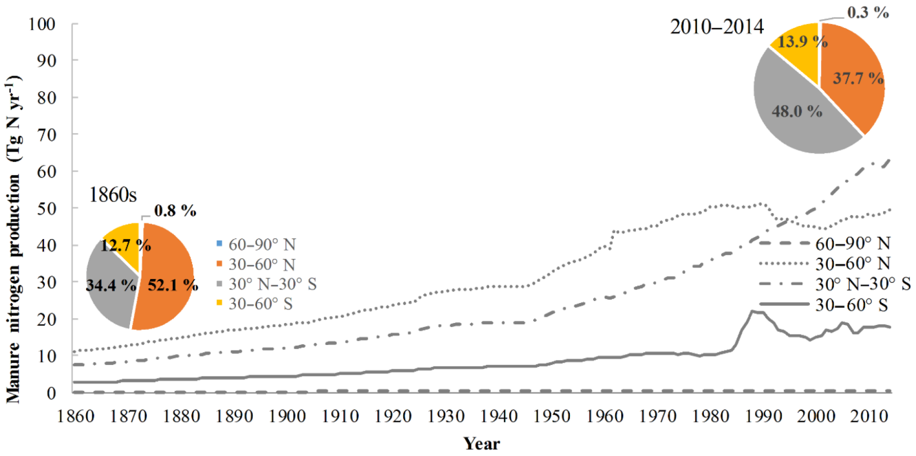

Figure 3. Estimation of global manure nitrogen production in northern high latitudes (60–90° N), northern midlatitudes (30–60° N), tropical regions (30° N–30° S), and southern midlatitudes (30–60° S).

global total manure production ($\sim 12.0 \pm 0.5$ Tg N yr^{-1}, average ±1 SD, same hereafter). Low-latitude regions (30° N–30° S) contributed one-third of total manure nitrogen production, followed by the southern midlatitudes (SM, 30–60° S; $\sim$ 12.7 %) and the northern high latitudes (NH, 60–90° N; $\sim$ 0.8 %). However, the dominant regions of the total manure nitrogen production have changed in recent years. During the most recent 5 years (2010–2014), low-latitude regions took the largest share, which was around 48.0 % of the estimated global manure production ($\sim 61.9 \pm 0.9$ Tg N yr^{-1}), followed by NM ($\sim$ 37.7 %), SM ($\sim$ 13.9 %), and NH, which contributed the least to the global manure nitrogen production (Fig. 3).

From a continental perspective, manure nitrogen production in Europe ($\sim 6.2 \pm 0.3$ Tg N yr^{-1}) appeared to be similar to that in Asia ($\sim 6.0 \pm 0.2$ Tg N yr^{-1}) in the 1860s, which was much higher than in any other continent, including South America ($\sim 3.6 \pm 0.1$ Tg N yr^{-1}), Africa ($\sim 2.8 \pm 0.1$ Tg N yr^{-1}), North America ($\sim 2.6 \pm 0.1$ Tg N yr^{-1}), and Oceania ($\sim 1.9 \pm 0.1$ Tg N yr^{-1}). During 2010–2014, however, Asia accounted for the largest single share ($\sim$ 34.2 %), followed by Africa ($\sim$ 17.6 %), South America ($\sim$ 14.2 %), Oceania ($\sim$ 13.3 %), Europe ($\sim$ 11.6 %), and North America ($\sim$ 9.2 %; Table 2).

Changes in manure nitrogen production showed high spatial variability and revealed several hotspots over the globe due to imbalances in global economic development and population growth (Fig. 4). Western Europe experienced an increase in the annual changing trend of manure nitrogen production from 1860 to the late 1980s and a decline thereafter. Southern Mexico, Central America, Columbia, southern Brazil, southeastern Australia, and India showed a continuing increasing trend for manure nitrogen production during 1860–2014. Western and eastern Africa and northeastern China experienced an increase in manure nitrogen production during recent decades.

3.3 Relative contribution of different livestock categories

At the global level, cattle dominated the manure nitrogen production among different livestock categories and contributed around 55.5 and 43.7 % of the total manure nitrogen production in 1860 and 2014, respectively (Figs. 5 and 6). Goats and sheep together contributed another one-third of the total manure nitrogen production during the study period, followed by swine and chickens. Ducks contributed the least to manure nitrogen production. However, at the regional level in terms of the dominant livestock species to the total manure nitrogen production, ducks were the dominant contributor in Alaska and Canada, while cattle played a dominant role in the conterminous United States, Mexico, India, and most areas in South America and Europe (Figs. 5 and 6). Goats contributed the most in North Africa, Australia, and central and northeastern Asia, while chickens and swine dominated in Russia. Over the study period, the relative contribution of cattle (dairy and other cattle) and sheep showed a significant decreasing trend to the total manure production, while for goats and chickens a significant increasing trend was found ($p < 0.001$; Fig. 6).

3.4 Spatial and temporal variation in manure nitrogen applied to cropland

At the global scale, the manure nitrogen applied to cropland increased from 3.6 Tg N in 1860 to 24.5 Tg N in 2014 with a significant increasing trend (0.14 Tg N yr^{-2}, $p < 0.01$) during 1860–2014. The application to cropland only accounted for 16.9–19.1 % of the total manure nitrogen production over the study period. Among different livestock categories, cattle (dairy and other cattle) contributed around half (42.4–

Table 2. Estimates of manure nitrogen production at the continental scale.

Manure nitrogen production ($\mathrm{Tg\,N\,yr^{-1}}$)	1860s	1900s	1940s	1980s	2010s
Asia	6.0 ± 0.2	9.8 ± 0.4	14.8 ± 0.7	29.3 ± 1.2	44.3 ± 0.7
North America	2.6 ± 0.1	4.2 ± 0.2	6.3 ± 0.3	10.7 ± 0.2	11.8 ± 0.04
Europe	6.2 ± 0.3	10.1 ± 0.4	15.3 ± 0.7	25.7 ± 0.1	14.9 ± 0.1
Africa	2.8 ± 0.1	4.6 ± 0.2	6 ± 0.4	13.3 ± 0.6	22.6 ± 0.8
South America	3.6 ± 0.1	5.9 ± 0.2	8.9 ± 0.4	14.4 ± 0.4	18.3 ± 0.1
Oceania	1.9 ± 0.1	3.1 ± 0.1	4.7 ± 0.2	13.0 ± 5.4	17.2 ± 0.1
Global	23.1 ± 1.0	37.5 ± 1.4	57.0 ± 2.8	106.4 ± 7.3	129.0 ± 1.5

Note: values indicate mean ± standard deviation of 10-year estimates.

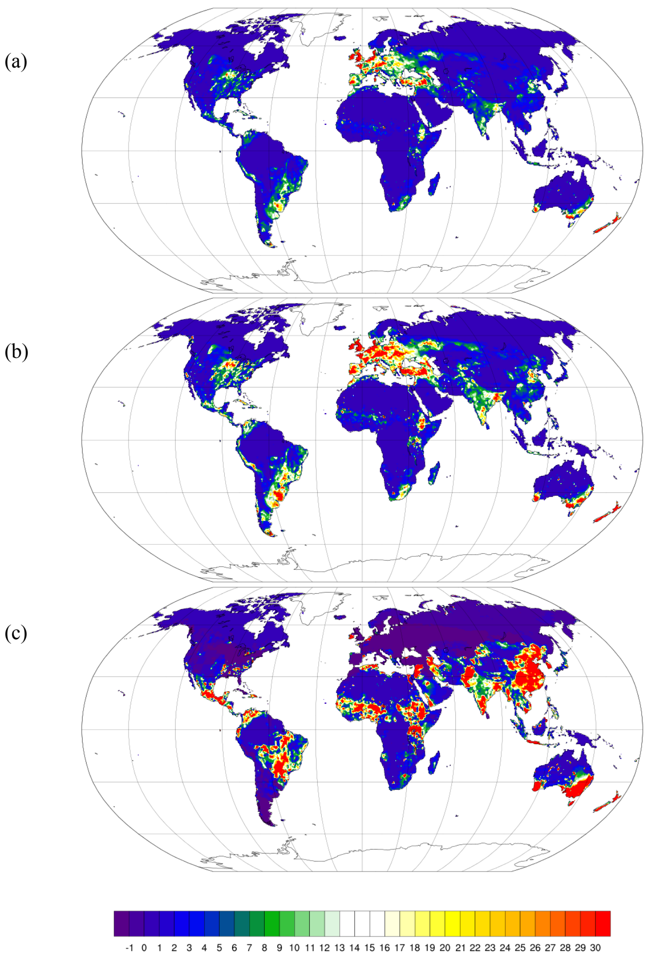

Figure 4. Spatial variation in the annual changing trend of manure nitrogen production ($\mathrm{kg\,N\,km^{-2}\,yr^{-1}}$) during **(a)** 1860–1910, **(b)** 1911–1960, and **(c)** 1961–2014.

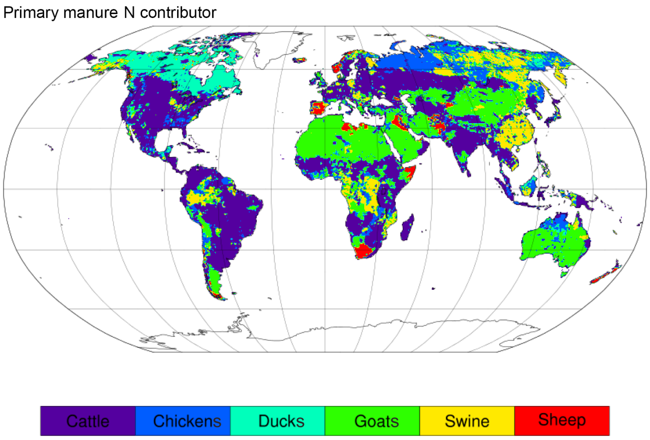

Figure 5. Spatial distribution of the primary contributors to manure nitrogen production in the year 2014.

58.7 %) of the total manure nitrogen applied to cropland. Other ruminants (goats and sheep) only accounted for 14.5–22.1 % over the study period, which was similar to the contribution from swine (16.9–23.3 %). At the continental scale, Europe was the dominant contributor (27.8–37.3 % of the global total) before the 1990s; however, its manure production has been reduced dramatically since the early 1990s (Fig. 7). Asia accounted for 24.4–37.7 % of the global manure nitrogen applied to cropland over the study period with the fastest growing rate of 0.47 $\mathrm{Tg\,N\,decade^{-1}}$ compared to other continents.

4 Discussion

4.1 Comparison with previous studies

Over the last 2 decades due to the recognition of the importance of manure nitrogen production in nitrogen cycles, various previous studies have estimated the manure nitrogen production at both regional and global levels. At the global scale, it has been suggested that manure nitrogen production increased from 26.3 $\mathrm{Tg\,N\,yr^{-1}}$ in 1860 to 142.5 $\mathrm{Tg\,N\,yr^{-1}}$ in

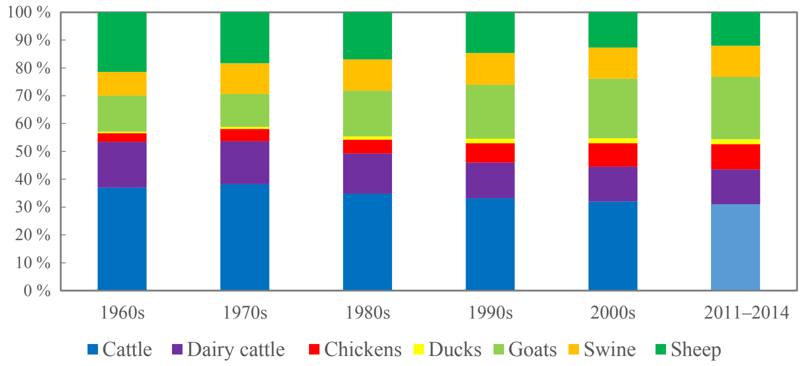

Figure 6. Relative contributions of different livestock animals to the total manure production.

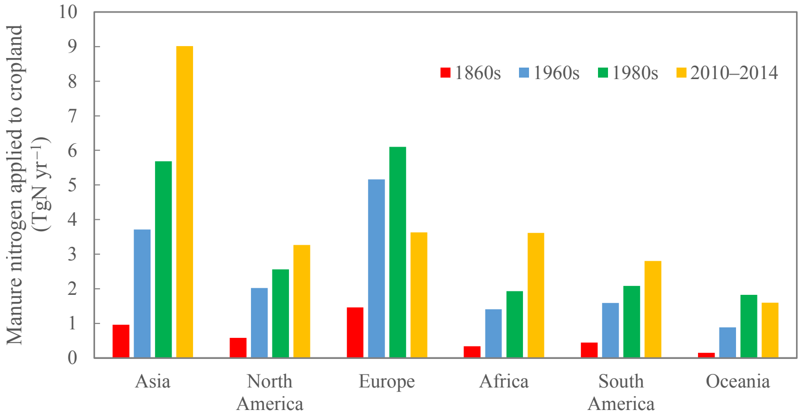

Figure 7. Changes in manure nitrogen amount applied to cropland at the continental level.

2004 with an increasing trend of 0.84 Tg N yr^{-1} (Holland et al., 2005), which was 18.5 % higher than our estimate from 1860 (~ 21.4 Tg N yr^{-1}) to 2004 (~ 119.1 Tg N yr^{-1}). However, our result during the 1990s (~ 110.0 ± 1.9 Tg N yr^{-1}) was more consistent with estimates from other studies, ranging from 101.4 to 128.3 Tg N yr^{-1} (Bouwman et al., 2009; Potter et al., 2010; Van der Hoek et al., 1999). There were some spatial differences between the estimated manure nitrogen application in this study and Bouwman et al. (2013) and manure nitrogen production in this study and Potter et al. (2010; Fig. 8), partly due to the difference in calculation processes. Bouwman's estimate for manure nitrogen applied to cropland is higher than our estimate, mainly due to the consideration of more refined manure management in different livestock production systems from our study. Gerber et al. (2016) and Carlson et al. (2017) suggested that only 7.4–7.8 Tg N yr^{-1} was applied to cropland, which is lower than our estimate. One big difference between our study and Gerber et al. (2016) and Carlson et al. (2017) is that we include the managed manure lost through leaching. Since their studies tried to estimate greenhouse gas emissions, it might be appropriate to remove all the lost N through different pathways, including leaching. However, here we try to estimate the total manure applied to cropland, so it may be more reasonable to account for this portion since the leaching processes occurred after manure was applied to soils.

Our analyses indicated that the total amount of manure production in different continents was close to other estimates with a difference of around ±4 % (difference = [estimate from this study − estimate from Potter et al. (2010)]/estimate from this study). Our results showed that manure nitrogen production in Europe started to decline in the early 1990s, which was mainly due to the reduction of livestock populations in Europe (FAOSTAT, 2014). At the country scale, our estimation of manure nitrogen production (~ 5.3 ± 0.8 Tg N yr^{-1}) was close to the previous estimation for the conterminous United States (~ 5.9 ± 0.7 Tg N yr^{-1}) during 1930–2012 (Yang et al., 2016). Meanwhile, both studies identified cattle as the dominant contributor to the manure nitrogen production in the conterminous United States. For the manure nitrogen applied to cropland and grassland in China, our estimation (3.0–3.6 Tg N yr^{-1}) was lower than previous studies (5.1–6.2 Tg N yr^{-1}) from 2002 to 2008 (Ouyang et al., 2013), which might be due to our consideration of livestock-specific and region-specific manure management factors to calculate the amount applied to cropland.

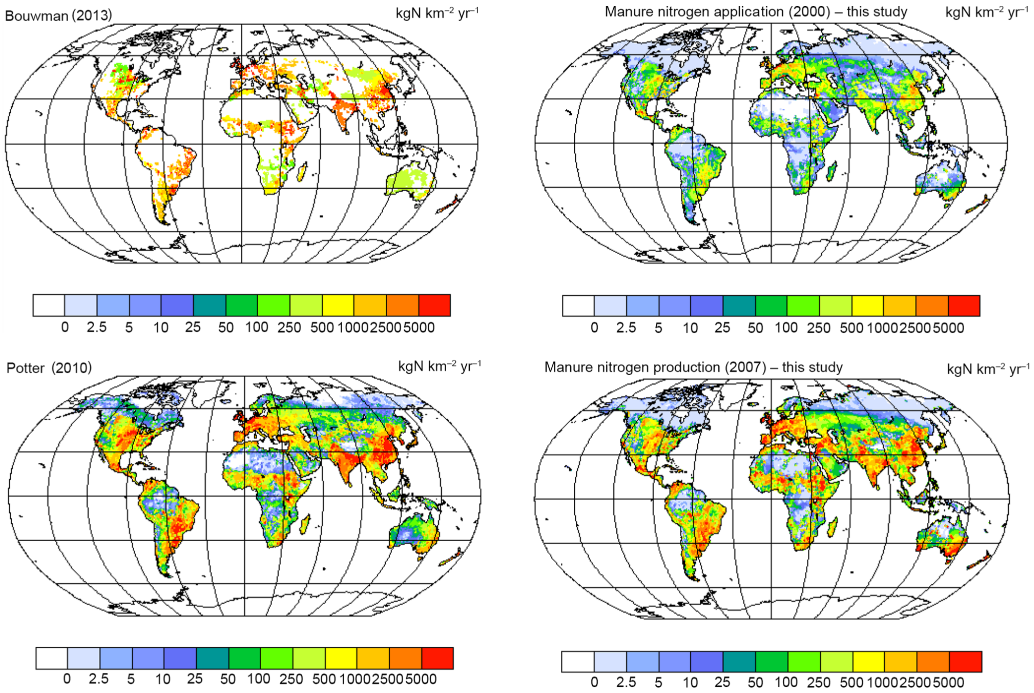

Figure 8. Comparison of manure nitrogen production estimated by Bouwman et al. (2013), Potter et al. (2010), and this study.

4.2 Manure production in the context of global environmental changes

During the past 155 years, the nitrogen input from atmospheric deposition has increased constantly with a significantly increasing rate of 0.36 Tg N yr^{-1} (Dentener, 2006; Wei et al., 2014). Nitrogen fertilizer use began and has altered the global nitrogen cycle since the early 1960s. Fertilizer use increased by 835 % during 1961–2013 with a significant increasing trend of 1.8 Tg N yr^{-1} (EPI, 2016). The magnitude of nitrogen production from manure was always higher than fertilizer consumption (Fig. 2) despite the fact that only 16.9–19.1 % of the total produced manure nitrogen could be applied to cropland. Previous studies suggested that manure nitrogen production is the single largest source of nitrous oxide emissions (Davidson, 2009; Davidson and Kanter, 2014). By using the regression equation derived by Davidson (2009), we could roughly estimate manure-induced N_2O emissions at around 2.7 Tg N_2O-N yr^{-1} in 2014, which accounted for 21.1 and 17.5 % of the total biogenic N_2O emissions estimated by a top-down approach and bottom-up approach, respectively (Tian et al., 2016).

4.3 Uncertainties

Our study estimates the magnitude and spatiotemporal distribution of manure nitrogen production over the globe during 1860–2014. There are several uncertainties that need to be considered while interpreting the results of this study. First, the livestock distribution was generated by using one-phase static GLIMS. Thus, the changes in the spatial distribution of livestock at the subnational level over time might not be accurate. For instance, free-grazing livestock may migrate due to the availability of food, especially in the early stage of the study period. Therefore, the spatial distribution of different livestock at the subnational scale, such as cattle, sheep, and goats, might be different considering livestock migration. Second, we assumed that the typical mass for different livestock from specific regions did not change over time. However, other studies have suggested that the carcass weights of chickens and beef cattle increased by about 30 % and the carcass weights of swine increased by about 20 % from the early 1960s to the mid-2000s (Thornton, 2010). Thus, manure nitrogen production may be overestimated in the past, and the relative contribution of cattle and chickens to the total manure production may be overestimated since their carcass weight grows much faster than other livestock. Third, the uniform excretion rate for specific livestock types at the regional scale could bring some uncertainties without considering the feed availability and quality across different seasons and various regions (Ouyang et al., 2013; Rufino et al., 2014). For example, Ouyang et al. (2013) provided the provincial N excretion rate in China, ranging from 53 to 94 kg N animal^{-1} yr^{-1} for dairy cattle and 17 to 36 kg N animal^{-1} yr^{-1} for other cattle. Velthof et al. (2015) suggested that the N excretion factors for EU countries using the gross N excretions in the Nitrates Directive reports was 75–184 and 20–90 kg N animal^{-1} yr^{-1} for dairy and other cattle, respectively. However, for most countries in the world, the N excretion rate at the regional scale is not available. In addition, we made several other assumptions to develop global datasets for manure nitrogen production and manure nitrogen applied to cropland due to the absence of appropriate datasets, which could introduce some uncertainties. For instance, we assumed that the spatial distribution of livestock production systems remained the same during 2006–2014. If more rangeland has been converted to cropland, the total amount of manure applied to cropland might be underestimated globally, except in North America. Additionally, we assumed that the irrigation area did not change before 1961. If less cropland was irrigated before, the manure application to cropland might be underestimated globally, except in Asia. When using this dataset for a specific purpose, further analyses or assumptions need to be made to fulfill the objectives of different studies (Yang et al., 2016). Reducing the associated uncertainty seems straightforward but is hard to accomplish at the current stage; it requires more available data, e.g., the detailed excretion rates for different livestock groups in a specific region over time or the spatial distribution of livestock and livestock systems at a finer scale with temporal variation. In addition, system thinking is another way to unravel complexity and explore options for sustainable development.

5 Data availability

The 5 arcmin gridded global dataset of manure nitrogen production and application in cropland is available at https://doi.org/10.1594/PANGAEA.871980 (Zhang et al., 2017). Data are in text/ASCII format. A supplemental file is added to the list of all other parameters used in this study to calculate the manure nitrogen production and the application in cropland.

6 Conclusion

In this study, we quantified the spatially explicit global manure nitrogen production across the globe during 1860–2014. The estimated total manure nitrogen production increased from 21.4 $\mathrm{Tg\,N\,yr^{-1}}$ in 1860 to 131.0 $\mathrm{Tg\,N\,yr^{-1}}$ in 2014 with an overall significant increasing trend during 1860–2014 (0.7 $\mathrm{Tg\,N\,yr^{-1}}$, $p < 0.01$). Along the latitudinal gradient, the low latitudes and northern middle latitudes dominated the estimated global manure nitrogen production. From a continental perspective, Asia contributed the largest portion of global manure nitrogen production during recent decades. Southern Mexico, Central America, Columbia, southern Brazil, Uruguay, Western Europe, India, northeastern China, and southeastern Australia increased most rapidly in manure nitrogen production during 1860–2014. We estimated that the manure nitrogen applied to cropland only accounted for 16.9–19.1 % of the total manure nitrogen production over the study period. Further studies are expected to comprehensively evaluate the tradeoff between food production, climate mitigation, and environmental pollution caused by the application of manure to further improve manure management. Together with other data, this 5 arcmin gridded dataset could be used as an input for ecosystem and Earth system models to assess the impact of manure production on global biogeochemical processes, water resources, and climate change.

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Competing interests. The authors declare that they have no conflict of interest.

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