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Projections of NH_3 emissions from manure generated by livestock production in China to 2030 under six mitigation scenarios

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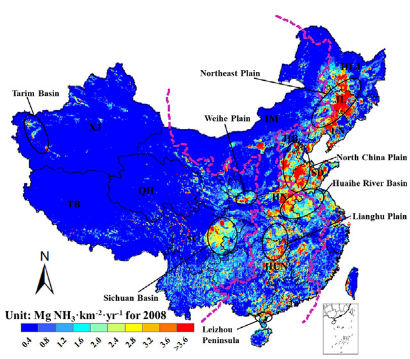
HIGHLIGHTS

- 1 km × 1 km gridded NH_3 emissions from China's livestock manure were estimated.
- Provincial condition-specific emission factors and county-level activity data were used.
- Emission trends and patterns were interpreted in light of government policies.
- NH_3 emissions were projected to year 2030 under six mitigation scenarios.
- Low NH_3 application was the most effective scenario for NH_3 mitigation.

GRAPHICAL ABSTRACT



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ABSTRACT

China's rapid urbanization, large population, and increasing consumption of calorie-and meat-intensive diets, have resulted in China becoming the world's largest source of ammonia (NH_3) emissions from livestock production. This is the first study to use provincial, condition-specific emission factors based on most recently available studies on Chinese manure management and environmental conditions. The estimated NH_3 emission temporal trends and spatial patterns are interpreted in relation to government policies affecting livestock production. Scenario analysis is used to project emissions and estimate mitigation potential of NH_3 emissions, to year 2030. We produce a 1 km × 1 km gridded NH_3 emission inventory for 2008 based on county-level activity data, which can help identify locations of highest NH_3 emissions. The total NH_3 emissions from manure generated by livestock production in 2008 were 7.3 Tg $NH_3 \cdot yr^{-1}$ (interquartile range from 6.1 to 8.6 Tg $NH_3 \cdot yr^{-1}$), and the major sources were poultry (29.9%), pigs (28.4%), other cattle (27.9%), and dairy cattle (7.0%), while sheep and goats (3.6%), donkeys (1.3%), horses (1.2%), and mules (0.7%) had smaller contributions. From 1978 to 2008, annual NH_3 emissions fluctuated with two peaks (1996 and 2006), and total emissions increased from 2.2 to 7.3 $Tg \cdot yr^{-1}$ increasing on average 4.4%$\cdot yr^{-1}$. Under a business-as-usual (BAU) scenario, NH_3 emissions in 2030 are expected to be 13.9 Tg $NH_3 \cdot yr^{-1}$ (11.5–16.3 Tg $NH_3 \cdot yr^{-1}$). Under mitigation scenarios, the projected emissions could be reduced by 18.9–37.3% compared to 2030 BAU emissions. This study improves our understanding of NH_3 emissions from livestock production, which is needed to guide stakeholders and policymakers to make well informed mitigation decisions for NH_3 emissions from livestock production at the country and regional levels.

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1. Introduction

Ammonia (NH_3) is the most abundant gaseous alkaline compound in the atmosphere (Behera et al., 2013). NH_3 reacts with sulfuric acid and nitric acid in the lower atmosphere to form secondary inorganic particulate matter with diameters ≤ 2.5 μm ($PM_{2.5}$), with subsequent adverse health and environmental effects, such as aggravation of respiratory disease symptoms (Pope et al., 2009) and visibility reduction (Ye et al., 2011). In addition, NH_3 and its secondary products add to the overall budget of atmospheric nitrogen (N) deposited and contribute to soil acidification (Guo et al., 2010), eutrophication (Paerl, 2002), and disruption of ecosystem functions (Stevens et al., 2004; Southon et al., 2013). Studies have shown that NH_3 emission reductions in the future could be a cost-effective control strategy for $PM_{2.5}$ compared to further controls on sulfur dioxide, and nitrogen oxides (Chang et al., 2016; Meng et al., 2017). Therefore, understanding NH_3 emissions from different sources, quantifying their magnitudes and evaluating mitigation options are the subject of scientific research, worldwide.

In the past three decades, China has been a main contributor of global economic growth and trade (United Nations, 2015). Increase in agricultural commodity consumption in China has worldwide economic and environmental effects (Paulot and Jacob, 2014). Global NH_3 emissions of natural and anthropogenic sources were estimated to be 53–55 $Tg \cdot yr^{-1}$, with an estimated contribution of 32% from livestock manure from 2008 to 2010 (EDGAR v4.3.1, 2017). Livestock manure contributed to an estimated 52% of the total NH_3 emissions in China for 2012 (Kang et al., 2016). Prior estimates of NH_3 emissions in China have adopted bottom-up approaches mainly based on statistical data available in official Chinese or intergovernmental organization databanks and use of emission factor (EF) values (Huang et al., 2012; Kang et al., 2016) or by inverse modeling, where emissions are constrained by observations of NH_3 atmospheric concentrations and wet deposition fluxes (Paulot et al., 2014). These studies represent best estimates up to the date they are compiled, with common limitations of data availability and accuracy, while the methods themselves may introduce biases in the magnitude of the emission estimates. Previous bottom-up studies have used provincial-level activity data (e.g., Gu et al., 2012; Kang et al., 2016). Compared to these studies use of county-level activity data can contribute to better identification of local hot spots (locations of highest NH_3 emissions) and decrease the uncertainties of spatial distribution of NH_3 emissions (Xu et al., 2016; Zhou et al., 2014). Uncertainties in estimates of NH_3 emissions from livestock manure for China are as large as 50% (Zhou et al., 2016). The limited spatiotemporal coverage by field measurements is an important factor contributing to uncertainty because of the high variability in local variables such as climate (Bouwman et al., 1997), soil properties (Clarisse et al., 2009), and animal manure management practices (Carozzi et al., 2013; Sun et al., 2016).

The objectives of this paper are to: 1) provide new NH_3 emissions from the Chinese livestock sector using higher spatial resolution activity data collected from 329 municipality registers than previous studies, and provincial condition-specific emission factors (EFs) updated with data from existing measurements of NH_3 emissions at each of the different stages of manure management, specific to Chinese manure management and environmental conditions; and 2) update projected NH_3 emissions from livestock production to year 2030, under six mitigation scenarios. To our knowledge, this is the first study that considers county-level activity data and region-specific conditions, in China. These are important for evaluating region-specific mitigation potential of NH_3 emissions in China's livestock production sector, projected to year 2030.

2. Methods

2.1. Estimation of NH_3 emissions

We adopted a bottom-up approach based on numbers of different categories of livestock and corresponding provincial condition-specific EFs to develop historical and future NH_3 emissions from manure generated by livestock production in China. The livestock categories considered in this study are pigs, dairy cattle, other cattle (beef cattle, buffalos, and draft cattle), sheep and goats (combined), poultry, horses, donkeys and mules. Total NH_3 emissions were calculated by the following equation:

$$E_{i,l} = \frac{17}{14} \cdot \sum_j AP_{j,l} \sum_i \sum_{s=1}^{4} \left[EF_{i,j,l,s} \cdot \left(1 - RE_{i,k,s}\right) \cdot IR_{i,j,k,l} \right] \quad (1)$$

where $E_{i,l}$ is the NH_3 emission in year l for a region i, Tg $NH_3 \cdot yr^{-1}$; i, j, k, and l represent region (county-level for 2008 and provincial-level for other years), livestock category, abatement technique, and year, respectively; 17/14 is the conversion coefficient of NH_3-N emissions to NH_3 emissions; AP is number of heads of species j; s represents emission during each of the stages of manure generated by livestock production; EF is the unabated NH_3-N EF, kg NH_3-N $head^{-1} \cdot yr^{-1}$; RE is the removal efficiency of abatement technique k; and IR is the implementation rate of the abatement technique k. If no abatement is applied, RE equals zero and IR is one. County-level NH_3 emissions in 2008 were further allocated to 1 km × 1 km spatial resolution based on proxy datasets recommended by previous studies (Huang et al., 2012; Zhou et al., 2014), as follows: cropland and grassland land cover were used as a proxy for NH_3 emissions from livestock manure field application and livestock outdoor/grazing (outdoor or grazing), respectively; and rural human population density was used to allocate livestock housing and manure storage emissions (RESDC, 2017).

2.2. Activity data

In this study, county-level for 2008 and provincial-level for 1978–2008 livestock population data were obtained for 2376 counties from 329 municipal statistical registers in mainland China, Hong Kong, Macau, and Taiwan (Hong Kong and Macau have no agriculture, and thus all of their activity data equal zero) and national statistics registers, respectively. The specific sources for the data are listed in Table 1. From these sources, we obtained the number of slaughtered pigs and poultry, for which the length of rearing period is <365 days; and the year-end stock number of dairy cattle, other cattle, sheep and goats, horses, donkeys and mules for which the rearing period is >365 days. We used annual population numbers of different livestock categories available at county-level for 2008 and provincial-level for 1978–2007. For counties or provinces where data were unavailable for certain years, data were derived by temporal interpolation (Zhou et al., 2014). Data quality was evaluated by sensitivity and uncertainty analysis following the same approach described in Xu et al. (2016).

2.3. Emission factors

In this study, the main flows of total ammoniacal nitrogen (TAN) were embodied in livestock manure, and the whole manure management chain - livestock excretion, outdoor/grazing, housing, manure storage and manure field application - in China was considered. TAN input into four different stages of manure management was estimated by rearing period, total daily amount of provincial-specific N excretion rate, provincial regional proportion of the free-range system and the percent of N in excreted feces transformed into TAN to develop Chinese provincial condition-specific TAN. Chinese provincial condition-specific NH_3 EFs were estimated from the above estimated Chinese provincial condition-specific TAN and reference TAN emission coefficients (ECs) for each manure management stage. ECs were obtained from experimental studies, expert judgments and review articles (Table S1). The total daily amount of provincial condition-specific N excretion rate (Table S2) was directly compiled from the results for the Livestock Manure Sector in the National Pollution Source Survey Database and measurements for China (SCC, 2013). Detailed description of the methods