Modeling the interinfluence of fertilizer-induced NH$_3$ emission, nitrogen deposition, and aerosol radiative effects using modified CESM2

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Abstract. Global ammonia (NH$_3$) emission is expected to continue to rise due to intensified fertilization for growing food to satisfy the increasing demand worldwide. Previous studies have focused mainly on estimating the land-to-atmosphere NH$_3$ injection but seldom addressed the other side of the bidirectional nitrogen exchange – deposition. Ignoring this significant input source of soil mineral nitrogen may lead to an underestimation of NH$_3$ emissions from natural sources. Here, we used an Earth system model to quantify NH$_3$-induced changes in atmospheric composition and the consequent impacts on the Earth’s radiative budget and biosphere as well as the impacts of deposition on NH$_3$ emissions from the land surface. We implemented a new scheme into the Community Land Model version 5 (CLM5) of the Community Earth System Model version 2 (CESM2) to estimate the volatilization of ammonium salt (NH$_4^+$) associated with synthetic and manure fertilizers into gaseous NH$_3$. We further parameterized the amount of emitted NH$_3$ captured in the plant canopy to derive a more accurate quantity of NH$_3$ that escapes to the atmosphere. Our modified CLM5 estimated that 14 Tg N yr$^{-1}$ of global NH$_3$ emission is attributable to fertilizers. We interactively coupling terrestrial NH$_3$ emissions to atmospheric chemistry simulations by the Community Atmospheric Model version 4 with chemistry (CAM4-chem), we found that such emissions favor the formation and deposition of NH$_4^+$ aerosol, which in turn influences the aerosol radiative effect and enhances soil NH$_3$ volatilization in regions downwind of fertilized croplands. Our fully coupled simulations showed that global-total NH$_3$ emission is enhanced by 3.3 Tg N yr$^{-1}$ when 30 % more synthetic fertilizer is used compared to the 2000-level fertilization. In synergy with observations and emission inventories, our work provides a useful tool for stakeholders to evaluate the intertwined relations between agricultural trends, fertilizer use, NH$_3$ emission, atmospheric aerosols, and climate so as to derive optimal strategies for securing both food production and environmental sustainability.

1 Introduction

Global NH$_3$ emission has risen from 59 to 65 Tg N yr$^{-1}$ during 2000–2008, driven mainly by the increasing fertilizer use and manure handling in farms and animal operations (Sutton et al., 2013). After entering the atmosphere, NH$_3$ gas readily neutralizes sulfuric acid (H$_2$SO$_4$) and nitric acid (HNO$_3$), which are derived from the oxidation of sulfur dioxide (SO$_2$) and nitrogen oxides (NO$_x$), forming inorganic sulfate–nitrate–ammonium (SNA) aerosols (Behera and Sharma, 2012). These secondary ammonium (NH$_4^+$)
allows daily monitoring of global NH\textsubscript{3} progress to address previous observational deficiencies and this new ensemble of satellite observations offers significant
3
of atmospheric NH\textsubscript{3} in 2000–2010 to 33–37 Tg N yr\textsuperscript{-1} (Sutton et al., 2013; Janssens-Maenhout et al., 2015; Hoesly et al., 2018). One of the state-of-the-art inventories, the Emissions Database for Global Atmospheric Research (EDGAR) version 4.3.2, provides global anthropogenic emission estimates in 1° × 1° resolution for the period 1970–2012 (Crippa et al., 2018). The accuracy of these inventories is not only affected by the integrity of the activity data surveyed but also constrained by the suitability of emission factors. Simply adopting emission factors from other countries may result in biases because of regional differences in technologies, farming practices, climate, and soil conditions (Huang et al., 2012). This pitfall has motivated the development of other national and regional inventories in the US (e.g., US Environmental Protection Agency, 2014), China (e.g., Zhang et al., 2018), and Europe (e.g., European Environment Agency, 2013). These emission inventories are useful tools for source apportionment and input data for forward models, but as the NH\textsubscript{3} emissions are prescribed they do not respond to changes in, for example, nitrogen deposition and meteorology, making them insufficient for models to represent the full dynamics of the NH\textsubscript{3} cycle.

The global NH\textsubscript{3} cycle has proven to be challenging to study because of the various feedback mechanisms within the Earth system. The reactive nature of NH\textsubscript{3} and the contribution of deposited NH\textsubscript{4}\textsuperscript{+} to the re-emission of NH\textsubscript{3} from natural and agricultural soils have created a convoluted relationship between emissions and deposition. NH\textsubscript{4}\textsuperscript{+} particles can be transported along with airflows and dispersed across a more extensive geographical range than the highly reactive gaseous NH\textsubscript{3}. Such transport can introduce large heterogeneity in the spatial distribution of reactive nitrogen, rendering it not only a local but also a pan-regional problem (Asman et al., 1998). Moreover, NH\textsubscript{3} volatilization is a temperature-dependent process, while the presence of atmospheric NH\textsubscript{3} affects the composition of aerosols and their radiative forcing, thus in turn modifying the Earth’s surface energy budget (Ansari and Pandis, 1998).
In this study, we hence aim to enable modeling of the land–atmosphere bidirectional exchange of NH₃ so that we can quantify the dynamically evolving NH₃ cycle and feedback mechanisms associated with it under a changing environment. We employed the Community Earth System Model version 2 (CESM2), which has state-of-the-art model components representing the land, atmosphere, sea ice, and oceans. These sub-models can run independently or in various coupled configurations (Hurrell et al., 2013). Many studies have employed CESM for studying processes in both the atmospheric and terrestrial nitrogen cycles, e.g., NOₓ and N₂O emission (Saikawa et al., 2013, 2014; Zhao et al., 2017), deposition (Lamarque et al., 2013), denitrification and nitrate leaching (Nevison et al., 2016), crop nitrogen uptake (Levis et al., 2018), and reactive nitrogen input to the ecosystem associated with synthetic and manure fertilizers (Riddick et al., 2018). Yet, these studies did not consider the dynamic bidirectional transfer of NH₃ and NH₄⁺ between the land and atmosphere. To add the dynamic cycle of NH₃ back to CESM2, we adopted a process-based approach to parameterize NH₃ emission from cropland soils, which is different from the bidirectional "voltage resistance" models (Zhu et al., 2015; Riddick et al., 2016; Pleim et al., 2019; Vira et al., 2020). Our approach determines the multistage processes of soil NH₄⁺ to NH₃, including adsorption, dissociation, and volatilization. The process-based nature of this scheme allows us to evaluate the response of NH₃ emission to soil climate, soil nitrogen content, fertilization, deposition, competition against other soil biogeochemical processes (nitrification, microbial uptake, etc.), and vegetation growth. Comparing to other approaches, our scheme, which borrowed from a biogeochemical model, DeNitrification–DeComposition (DNDC), requires variables that are mostly already modeled in CLM5, allowing us to largely capture the dynamic nature of NH₃ emission. We also developed a prognostic parameterization for canopy capture of NH₃ instead of using a fixed generic value, e.g., one constant canopy reduction factor for all plants as used in some other studies (e.g., Riddick et al., 2016; Bouwman et al., 1997). Implementing these new schemes in the Community Land Model version (CLM5) (Lawrence et al., 2019), we could then estimate the emission associated with fertilizer use and perform fully coupled simulations with the Community Atmosphere Model version 4 with Chemistry (CAM4-chem) (Lamarque et al., 2012) that allow two-way exchange of NH₃ bridged by online emission and deposition to understand the subsequent effects on aerosol formation, climate, terrestrial ecosystems, and crop growth. We also compared our results with available emission inventories to evaluate model accuracy and uncertainty.

This paper demonstrates a framework that could help unfold the complicated interactions between fertilizer use, NH₃ emission, aerosol formation, climate, terrestrial ecosystems, and crop production. For instance, a recent study based on our model framework showed that enhanced nitrogen deposition induced by future fertilizer use could modify the meteorological environment via changes in vegetation and soil biogeochemistry and modulate future ozone pollution (Liu et al., 2021).

2 Methods

2.1 Community Earth System Model

We introduced new functionalities into CESM2 to enable the simulation of a coupled land–atmosphere nitrogen cycle and to further investigate the impacts of fertilizer-induced NH₃ emission on atmospheric composition, terrestrial biogeochemistry, and climate change. In particular, we implemented into CLM5 new parameterization schemes to quantify NH₃ volatilized from soil due to fertilizer application and captured by plant canopies. We further bridged CLM5 and CAM4-chem to enable two-way exchange of soil NH₃ emission and deposition of NH₃ to model a fully coupled, prognostic land–atmospheric NH₃ cycle.

Our model development was based on CLM5 with active biogeochemical cycles and a crop sub-model (CLM5-BGC-Crop, or CLM5 for short), which represents terrestrial carbon and nitrogen cycling with prognostic vegetation and crop growth. The model uses a sub-grid hierarchy (from grid cells, land units, columns, to patches) to capture the biogeophysical and biogeochemical differences between various land types within a model grid cell. In particular, CLM5 handles natural soil and croplands differently: multiple natural vegetation and crop units, columns, to patches) to capture the biogeophysical and biogeochemical differences between various land types within a model grid cell. In particular, CLM5 handles natural soil and croplands differently: multiple natural vegetation and crop units, columns, to patches) to capture the biogeophysical and biogeochemical differences between various land types within a model grid cell. In particular, CLM5 handles natural soil and croplands differently: multiple natural vegetation and crop units, columns, to patches) to capture the biogeophysical and biogeochemical differences between various land types within a model grid cell. In particular, CLM5 handles natural soil and croplands differently: multiple natural vegetation and crop units, columns, to patches) to capture the biogeophysical and biogeochemical differences between various land types within a model grid cell.
The manure fertilizer application rate is assumed constant for all crops at 2 g N m\(^{-2}\) yr\(^{-1}\), the same as the model default (Lombardozzi et al., 2020). All added depositional and fertilizer N is added to the soil NH\(_4\)\(^+\) pool of each layer from ground surface to 0.4 m underground according to a model-defined soil profile (Table S1) (Lawrence et al., 2018). Crops are harvested once they reach maturity or after a predefined maximum number of growing days (typically 150–165 d) (Lawrence et al., 2018).

In addition to the NH\(_3\) schemes, we also modified CLM5 to better simulate the terrestrial nitrogen cycle, specifically on the emission of NO\(_x\) from denitrification and nitrification and microbial mineralization of soil nitrogen. These modifications are documented in the Supplement.

### 2.2 Soil ammonia emission and canopy capture

Figure 1 summarizes the primary pathways of the terrestrial nitrogen cycle in CLM5. The model tracks nitrogen content in soil, plant, and organic matter as an array of separate nitrogen pools and biogeochemical processes as exchange fluxes of nitrogen between these pools. Soil mineral nitrogen, NH\(_4\)\(^+\), and NO\(_3\)\(^-\) compete for among plant uptake, microbial immobilization, nitrification, and denitrification based on the relative demand from each process. Release of nitrous oxide (N\(_2\)O) and NO\(_x\), as byproducts of nitrification and denitrification and leaching of soil nitrate also deplete soil NH\(_4\)\(^+\) and NO\(_3\)\(^-\), which can be replenished by fertilization and deposition of atmospheric NH\(_3\) and NO\(_3\). The deposition rates were prescribed in the default configuration and dynamically computed by CAM4-chem in our version. Other sources of soil mineral nitrogen include biological fixation by microbes or soybean and decomposition of plant litter and soil organic matter. Our proposed NH\(_3\) emission scheme was borrowed from a standalone biogeochemical model, DNDC version 9.5 (Li et al., 2012; Gilhespy et al., 2014; source code of DNDC v9.5 provided by Changsheng Li via personal communication on 18 June 2015), which has been extensively used for studying agricultural NH\(_3\) emission (e.g., Li et al., 2012; Balasubramanian et al., 2015, 2017; Zhang and Niu, 2016).

Following the treatment in DNDC, our scheme considered NH\(_3\) volatilization a multistage process and estimated the potential soil NH\(_3\) prone to emission (\(F_{\text{soil, pot}}\) g N m\(^{-2}\)) based on soil NH\(_4\)\(^+\) content. In each soil layer of a column or patch

\[
F_{\text{soil, pot}} = \left[\text{NH}_4^{+}\text{soil}\right] \times (1 - f_{\text{ads}}) \times f_{\text{dis}} \times f_{\text{vol}},
\]

where \(\text{NH}_4^{+}\text{soil}\) (g N m\(^{-2}\)) is the amount of soil NH\(_4\)\(^+\), \(f_{\text{ads}}\) accounts for the portion of NH\(_4\)\(^+\) adsorbed onto the surface of the soil matrix, \(f_{\text{dis}}\) is the fraction of the non-adsorbed NH\(_4\)\(^+\) that dissociated into aqueous NH\(_3\), and \(f_{\text{vol}}\) is the fraction of aqueous NH\(_3\) volatilized as gaseous NH\(_3\). The adsorbed fraction \(f_{\text{ads}}\), which is also bounded between 0 and 1, is given by Li et al. (1992) and Dutta et al. (2016):

\[
f_{\text{ads}} = 0.99(7.2733 f_{\text{clay}}^3 - 11.22 f_{\text{clay}}^2 + 5.7198 f_{\text{clay}} + 0.0263),
\]

where \(f_{\text{clay}}\) is the soil clay fraction as prescribed by the CLM5 surface data (Bonan et al., 2002); we adopted a factor of 0.99 instead of the one reported in Dutta et al. (2016), as per the source code of DNDC.

The non-adsorbed NH\(_4\)\(^+\) dissociates reversibly into aqueous NH\(_3\) and hydrogen ions (NH\(_3\)\(_{\text{aq}}\), NH\(_3\)\(_{\text{aq}}\) + H\(^+\)), and hence, \(f_{\text{dis}}\) is determined by the following equations (Li et al., 2012; Sutton, 1990; Sutton et al., 1993):

\[
f_{\text{dis}} = \frac{K_w}{K_a [H^+]}
\]

\[
K_w = 10^{0.08946 + 0.3605\left[\text{C}^{-1}\right]T_{\text{soil}}} \times 10^{-15}
\]

\[
K_a = (1.416 + 0.01357\left[\text{C}^{-1}\right]T_{\text{soil}}) \times 10^{-5}
\]

\[
[H^+] = 10^{-\text{pH}},
\]

where \(K_a\) (mol L\(^{-1}\)) and \(K_w\) (mol L\(^{-2}\)) are dissociation constants for NH\(_3\)\(_{\text{aq}}\) and NH\(_3\) as well as hydrogen- and hydroxide-ion equilibria, respectively; \(T_{\text{soil}}\) (°C) is soil temperature; and [H\(^+\)] (mol) is the concentration of aqueous hydrogen ion in the soil calculated from soil pH. CLM5 is currently not capable of calculating soil pH implicitly, so we performed our simulations using a constant pH of 6.5 for a more focused analysis. This pH value is consistent with the value used in the nitrification and denitrification schemes in CLM5. We further evaluated the uncertainty induced by our choice of pH and presented the sensitivity test results in the Supplement. Briefly, a higher pH would promote the model NH\(_3\) emission rate exponentially as the emission rate is of the order of 10\(^{\text{pH}}\). This high sensitivity warrants the need to include crucial chemical processes in the model for accurately determining soil pH online.

Lastly, we used this equation to calculate \(f_{\text{vol}}\) (Li et al., 1992; Gardner, 1965; source code of DNDC v9.5):

\[
f_{\text{vol}} = \left\{\frac{1.5s}{l[\text{m s}^{-1}] + s}\right\} \times \left(\frac{T_{\text{soil}}}{50[\text{°C}]+T_{\text{soil}}}\right) \times \left(\frac{l_{\text{max}} - l}{l_{\text{max}}}\right),
\]

where \(s\) (m s\(^{-1}\)) is surface wind speed; \(T_{\text{soil}}\) (°C) is soil temperature; and \(l\) and \(l_{\text{max}}\) (both in meters) are the depth of each soil layer and the maximum depth of a soil column, respectively. Our scheme assumes that vaporized soil NH\(_3\) in a deeper layer diffuses upward to the surface but does not explicitly simulate the process. Instead, it is represented in the last term in Eq. (7) as a ratio of \((l_{\text{max}} - l)/l\) for the NH\(_3\)\(_{\text{g}}\) contained in each soil layer. Hence, soil NH\(_4\)\(^+\) in deeper layers is also subject to loss to NH\(_3\) volatilization but at much slower rates than that in the upper layers. Details of the soil profile are provided in Table S1.
The actual soil NH$_3$ to be emitted ($F_{\text{soil,act}}$; g N m$^{-2}$) from each soil layer is then determined as

$$F_{\text{soil,act}} = \min \left(F_{\text{soil,pot}}, [\text{NH}_4^+]_{\text{available}} \right), \quad (8)$$

where $F_{\text{soil,pot}}$ is from Eq. (1), and $[\text{NH}_4^+]_{\text{available}}$ (g N m$^{-3}$) is the concentration of available soil NH$_4^+$ in the soil layer. The model distributes available soil NH$_4^+$ to all competing processes, namely NH$_3$ emission, plant uptake, microbial immobilization, and nitrification, according to their relative demands (individual potential flux to sum of all four potential fluxes) without bias toward any process (Lawrence et al., 2019). The column-level actual soil NH$_3$ prone to emission ($F_{\text{soil}}$; g N m$^{-2}$) is then computed as the sum of the product of $F_{\text{soil,act}}$ and the soil layer thickness (in meters) across all vertical layers.

Finally, assuming such NH$_3$ is released to the atmosphere at a constant rate over a model time step size ($\Delta t = 1800$ s in this study), our model estimates the NH$_3$ emission flux ($\dot{F}_{\text{soil}}$; g N m$^{-2}$ s$^{-1}$) as

$$\dot{F}_{\text{soil}} = \frac{F_{\text{soil}}}{\Delta t}. \quad (9)$$

If vegetation is present above the soil, some of the emitted NH$_3$ can be retained by the plant canopy, which is known to be related to the adsorption of hydrophilic NH$_3$ onto the leaf surface and molecular diffusion via the leaf stomata (Van Hove et al., 1987). Some studies represented the amount of captured NH$_3$ using constant scaling factors (e.g., 0.6 for all vegetation in Riddick et al., 2016; 0.8, 0.5, and 0.2 for tropical rainforests, other forests, and all other vegetation types, respectively, in Bouwman et al., 1997). Here, we calculated the flux of NH$_3$ captured by the canopy following the equation used in DNDC that accounts for the change in in-canopy NH$_3$ concentration, deposition velocity of ammonia, leaf area index (LAI), and air moisture (Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, 2017). To include the dynamic growth of crop canopy, we further adopted the canopy height adjustment factor employed by the Community Multiscale Air Quality (CMAQ) regional chemical transport model (Pleim et al., 2013). The portion of NH$_3$ flux from the soil that is not captured by plant canopies ($\dot{F}_{\text{atm}}$; g N m$^{-2}$ s$^{-1}$) is thus

$$\dot{F}_{\text{atm}} = \dot{F}_{\text{soil}} (1 - f_{\text{can}}) \quad (10)$$

$$f_{\text{can}} = \frac{L}{s_{10}} v_c \phi_c b (h_{\text{top}} - h_{\text{bot}}), \quad (11)$$

where $L$ is one-sided snow-free LAI; $s_{10}$ is the wind speed (m s$^{-1}$) at 10 m height; $v_c$ is the deposition velocity of NH$_3$ (0.05 m s$^{-1}$ as in DNDC); $\phi_c$ is in-canopy relative humidity; $b$ is a correction factor for the effect of canopy thickness (14 m$^{-1}$ is used here as suggested by Pleim et al., 2013); and $h_{\text{top}}$ and $h_{\text{bot}}$ are heights of canopy top and bottom (both in meters), respectively. Except for $v_c$ and $b$, all variables are...
calculated within CLM5 (see Lawrence et al., 2019, for detailed calculation methods). These two equations estimate the concentration of NH$_3$ exposed to plant canopy under a given soil emission rate at each time step: dividing soil NH$_3$ emission rate by $s_{10}$ gives an approximate in-canopy NH$_3$ concentration, and multiplying the latter with $v_c$ and $L$ produces an estimated quantity of NH$_3$ retained by the canopy. The last three terms account for the influence of in-canopy moisture and canopy thickness on the effectiveness of canopy capturing. We used $F_{atm}$ as an input of the ammonia emissions to drive chemistry calculations in CAM4-chem. The captured NH$_3$ can re-enter the soil surface along with water throughput or be metabolized by the plants if it diffuses into the leaf tissues (Hutchinson et al., 1972). Since the detailed mechanisms are still uncertain and beyond the focus of this study, we decided to assume that all captured NH$_3$ returns to the soil directly as NH$_4^+$ and discuss how it will affect our analysis in the “Conclusions” section.

2.3 Simulations of the land–atmosphere NH$_3$ cycle

For the atmospheric component, we employed CAM4-chem (Lamarque et al., 2012), with chemistry based on the tropospheric chemistry mechanism of MOZART-4 (Emmons et al., 2010). CAM4-chem employs a bulk aerosol approach and predicts the formation of PM$_{2.5}$ components including SO$_4^{2-}$, NO$_3^-$, and NH$_4^+$, where the injection rates of precursors – sulfur dioxide (SO$_2$), NO$_x$, and NH$_3$ – are prescribed by the Coupled Model Intercomparison Project phase 6 (CMIP6), also known as the Community Emissions Data System (CEDS) emission inventory (CMIP6 hereinafter) for anthropogenic activities (Hoesly et al., 2018). The biomass burning emissions used for our simulations are described by von Marle et al. (2016, 2017) and are all assumed as surface emissions without plume rise or predefined vertical distribution. Biogenic emissions, e.g., of isoprene, are updated online from CLM5 using the Model of Emissions of Gases and Aerosols from Nature (MEGAN) version 2.1 (Guenther et al., 2012). In our coupled simulations, we substituted the portion of NH$_3$ emission associated with fertilizers from the CAM4-chem inventory input (CESD) for our online simulated emission rates from CLM5. This study did not consider manure spreading on pastures and grazing animals. Atmospheric NH$_3$ and NH$_4^+$ formed sequentially return to CLM5 through deposition. We note that the NO$_x$ emission inputs for CAM4-chem were solely from the emission inventories and did not include those from our modified denitrification and nitrification schemes.

Dry deposition in CAM4-chem is handled using the resistance approach (Wesely, 1989; Emmons et al., 2010). For NH$_3$ vapor, the model calculates the aerodynamic and the boundary-layer (laminar sublayer) resistance based on the online atmospheric dynamics, while the surface resistance over land is determined according to the online CLM5 surface variables, e.g., canopy height and LAI, as well as a species-specific reactivity factor for oxidation and effective Henry’s law coefficients. For particle-phase NH$_4^+$, the aerodynamic resistance is the same as that of NH$_3$, but the boundary-layer and surface resistances are replaced by a single resistance term that depends on the surface friction velocity. The deposition velocities of NH$_3$ and NH$_4^+$ are the reciprocal of the sum of their corresponding resistance terms, and their deposition rates are the product of their deposition velocities and concentrations. Wet deposition in CAM4-chem follows the Neu and Prather (2012) scheme, which assumes a first-order loss of chemicals due to in-cloud and below-cloud scavenging processes. The wet deposition rates of NH$_3$ and NH$_4^+$ are the products of their concentration, their loss frequencies (based on their Henry’s law coefficients), and the fraction of the grid box subject to scavenging (e.g., cloudy or raining). These NH$_4^+$ deposition fluxes (together with NO$_x$) then become the input to CLM5 for the soil NH$_4^+$ pool (Lawrence et al., 2018).

In the default configuration, atmospheric chemistry interacts with the climate solely through radiation in CAM4-chem (Lamarque et al., 2012). Furthermore, atmospheric reactive nitrogen (NH$_4^+$ or NO$_3^-$) does not directly interact with radiative transfer in the model. Instead, its radiative implications are manifested via altering the gas–aqueous partitioning of sulfate (Emmons et al., 2010; Metzger, 2002) and the subsequent changes in direct radiative effect due to any changes in sulfate aerosols. The subsequent sulfate-induced changes in cloud optical properties (indirect radiative effect) were not considered in this work. A detailed description of the radiative transfer processes in CAM4-chem is provided in Neale et al. (2010).

Recent studies on NH$_3$ emission using CESM2 (e.g., Riddick et al., 2016, and Vira et al., 2020) focused only on the one-way land-to-atmosphere flux of NH$_3$ while neglecting the enhancing effect of nitrogen deposition on NH$_3$ emission. By coupling CLM5 and CAM4-chem, we allowed the model land–atmosphere NH$_3$ cycle to evolve in response to any changes in the bidirectional exchange of NH$_3$ and NH$_4^+$ via online emission and deposition. It also makes our method more suitable than a one-way model for studying the feedback effects of future changes in climate and agricultural activities on the biogeochemical cycles.

Table 1 provides configuration details of our experiments. CAM4_CLM5_2000 and CAM4_CLM5_2050 encapsulated the full functionality of our implementation, i.e., CAM4-chem receives the online CLM5 NH$_3$ emission rates as input to predict atmospheric NH$_3$ concentration, the subsequent formation of secondary ammonium aerosols (modeled as changes in sulfate aerosols in the model), and the corresponding instantaneous sulfate aerosol radiative effect, whilst CLM5 obtains the online CAM4-chem dry and wet deposition rates of NH$_3$ and NO$_x$ to calculate the addition of soil NH$_4^+$ via deposition. The deposited nitrogen will eventually enrich soil fertility and fuel the re-emission of soil NH$_3$, while the aforementioned aerosol radiative effect.
can cool the Earth’s surface and suppress NH3 volatilization. The [CAM4_CLM5_NDEP] cases were set to isolate the impact of NH3 deposition on NH3 emission and crop growth. In this setup, CAM4-chem used prescribed gases (except for water vapor) and aerosols in the radiation transfer calculation (i.e., aerosol–radiation interaction is disabled). Hence, any changes in the atmospheric sulfate aerosol loading induced by the addition of or reduction in NH3 would not affect radiative transfer. We note that the differences in radiative budget between the [CAM4_CLM5_NDEP] and other configurations with aerosol–radiation interaction enabled would include the effects attributable to both NH3-induced sulfate changes and the differences in spatial distribution between the prescribed and prognostic aerosols. For instance, the differences between [CAM4_CLM5_NDEP] and [CAM4_CLM5] are substantial for sulfate (up to 4 % in zonal mean mass ratio; mostly inland) and dust (up to 30 % zonally; mostly in sub-Saharan Africa and other desert regions) and are unlikely related to NH3 changes; meanwhile, the differences are rather negligible for organic carbon, black carbon, and sea salt. This configuration was intended to isolate the enhanced fertilization effect of N deposition. Similarly, [CAM4_CLM5_CLIM] cases were prescribed with constant nitrogen deposition fluxes so that we could quantify the impacts of the changes in instantaneous aerosol radiative effects. We hypothesized that an increased NH3 emission would promote the formation of sulfate aerosols, and the subsequent aerosol cooling effect would be observed in this setup. Finally, we further evaluated the impacts of intensive fertilizer use to promote agricultural production in the future as projected by FAO (2007) by repeating the first three simulations with fertilization at present-day (2000; model default) and future (2050; assuming 30 % more synthetic fertilizers, while manure fertilizer is kept at 2000 level) rates. We note that further increases in agricultural production might also involve cropland expansion, but such a practice was not included in this study.

All simulations were run for 30 years using the spun-up year 2000 initial conditions with the corresponding land cover data provided out of the box by CLM5. The first 10 years of outputs were used to further stabilize the model (such that the interannual variability in the emission fluxes could be < ±10 %) after our ammonia scheme was implemented. Our analysis in the next section focuses on the averages of the last 20 years of simulated results to minimize influence from any long-term meteorological variability. Only the atmosphere (CAM4-chem) and the land (CLM5) components were active. CAM4-chem was run with free dynamics in the standard spatial resolution of 1.9° × 2.5° horizontally with 27 vertical layers (from surface to ~ 40 km). CLM5 was run in the same horizontal resolution with 25 soil layers down to ~ 50 m below ground. Sea surface temperature (SST) and sea ice conditions (Hurrell et al., 2008) as well as the mixing ratios of greenhouse gases (Meinshausen et al., 2017) were all fixed at the 2000 levels. Our analysis focuses on the changes in fluxes of soil biogeochemical processes, the evolution of atmospheric NH3, the sequential changes in sulfate aerosols, and the influence of the bidirectional NH3 exchange on crop production.

2.4 Datasets for model validation

We also compared our simulation results with various available global observations and emission inventories. CLM5-modeled NH3 emission was compared with multiple emission inventories including CMIP6, EDGAR, and the Magnitude and Seasonality of Agricultural Emissions for NH3 (MASAGE). CAM4-chem-simulated atmospheric NH3 using CLM5 NH3 and CMIP6 was compared against the satellite-derived IASI NH3 concentration field (gridded and reported in Van Damme et al., 2018a). Details of these datasets are tabulated in Table 2. The datasets were regressed to match our model resolution of 1.9° × 2.5° using bi-linear interpolation. We note also that model–inventory comparisons are not meant to be exact given that our simulations were performed using free-running dynamics and thus did not necessarily match the meteorological years of the inventories, and the synthetic fertilizer use was not identical to the ones assumed when inventories were compiled. Thus, these results are presented as qualitative comparisons to indicate where our estimation is consistent with the inventories and where it is not.

3 Results

3.1 Fertilizer-induced NH3 emission

We first evaluated the fertilizer-induced NH3 emission simulated by the fully coupled land–atmosphere simulation, [CAM4_CLM5_2000]. Figure 2 shows the annual-total global NH3 emission at above-canopy level from different land types averaged over the remaining 20 years of simulation. We also compared our NH3 emission with inventory estimates reported by CMIP6 (Hoesly et al., 2018), EDGAR v4.3.2 (Crippa et al., 2018), and MASAGE (Paulot et al., 2014). We extracted the monthly fertilizer-induced NH3 emission estimates from MASAGE and assumed that one-third of the total agricultural NH3 emission reported by CMIP6 and EDGAR is associated with synthetic fertilizer, which is consistent with the apportionment reported in previous studies and environmental reports (Paulot et al., 2014; Riddick et al., 2016; National Oceanic and Atmospheric Administration, 2000; European Environment Agency, 2010; Gu et al., 2012; Paulot et al., 2015; Zheng et al., 2017).

Regional emission totals are summarized in Table 3. A grid-cell-by-grid-cell model–inventory spatial comparison of the annual-total NH3 emission rates was conducted by computing Pearson’s correlation coefficients (R) and slopes (β) of linear regression using the reduced major axis method as well as normalized mean biases (NMBs; Σ(Mi −


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Table 1. Details of simulation designs.

<table>
<thead>
<tr>
<th>Alias</th>
<th>Synthetic fertilizer usage</th>
<th>Fertilizer-induced NH₃ emission</th>
<th>N deposition</th>
<th>Aerosol–radiation interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAM4_CLM5_2000</td>
<td>Same as 2000 level</td>
<td>Modified CLM5 in this study</td>
<td>Dynamic</td>
<td>Enabled</td>
</tr>
<tr>
<td>CAM4_CLM5_2050</td>
<td>30% more than 2000 level</td>
<td>Modified CLM5 in this study</td>
<td>Dynamic</td>
<td>Enabled</td>
</tr>
<tr>
<td>CAM4_CLM5_NDEP_2000</td>
<td>Same as 2000 level</td>
<td>Modified CLM5 in this study</td>
<td>Dynamic</td>
<td>Disabled</td>
</tr>
<tr>
<td>CAM4_CLM5_NDEP_2050</td>
<td>30% more than 2000 level</td>
<td>Modified CLM5 in this study</td>
<td>Dynamic</td>
<td>Disabled</td>
</tr>
<tr>
<td>CAM4_CLM5_CLIM_2000</td>
<td>Same as 2000 level</td>
<td>Modified CLM5 in this study</td>
<td>Dynamic</td>
<td>From [CAM4_CLM5] assuming 2000-level fertilization</td>
</tr>
<tr>
<td>CAM4_CLM5_CLIM_2050</td>
<td>30% more than 2000 level</td>
<td>Modified CLM5 in this study</td>
<td>Dynamic</td>
<td>From [CAM4_CLM5] assuming 2000-level fertilization</td>
</tr>
<tr>
<td>CAM4_CMIP6_2000</td>
<td>Same as 2000 level</td>
<td>CMIP6 inventory</td>
<td>Dynamic</td>
<td>Enabled</td>
</tr>
</tbody>
</table>

Table 2. Details of observations and emission inventories used in this study for model comparison and validation.

<table>
<thead>
<tr>
<th>Name</th>
<th>Coverage</th>
<th>Resolution</th>
<th>Period of data</th>
<th>Data type: sources extracted for model comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>MASAGE</td>
<td>Global</td>
<td>0.5° × 0.5° monthly mean</td>
<td>2006</td>
<td>Emission inventory: NH₃ emission from agricultural soil associated with synthetic fertilizer only</td>
</tr>
<tr>
<td>(Paulot et al., 2014)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EDGAR</td>
<td>Global</td>
<td>0.1° × 0.1° monthly mean</td>
<td>2010</td>
<td>Emission inventory: NH₃ emission from agricultural soil with both synthetic and manure fertilizers</td>
</tr>
<tr>
<td>(Crippa et al., 2018)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMIP6</td>
<td>Global</td>
<td>0.01° × 0.01° monthly mean</td>
<td>2000–2015</td>
<td>Emission inventory: NH₃ emission from agricultural soil with both synthetic and manure fertilizers</td>
</tr>
<tr>
<td>(Hoesly et al., 2018)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IASI</td>
<td>Global</td>
<td>0.01° × 0.01° annual mean</td>
<td>2008–2016</td>
<td>Satellite-based measurement: column NH₃ density</td>
</tr>
<tr>
<td>(Van Damme et al., 2018a)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$O_i)/\Sigma(O_i)$, where $M_i$ and $O_i$ are simulated and inventory NH₃ emission in each grid cell) and mean fractional biases (MFBS; $2\Sigma\left[(M_i - O_i)/(M_i + O_i)\right]/N$, where $N$ is the number of grid cells). A summary of these statistics is shown in Fig. 2a. We also computed the $R$ values between the monthly emission rates computed by CLM5 (as in the fully coupled case, [CAM4_CLM5_2000]) and each inventory for each grid cell (see Fig. 2d, f, and h). We highlighted with overlying black dots the grid cells with high coefficients of determination, which are statistically significant (i.e., $R^2 > 0.5$ and $p < 0.05$), indicating where our simulation can reproduce more than half of the variability in the inventory estimates.

Globally, CLM5 estimates that the annual-total fertilizer-induced NH₃ emission reaches 14 Tg N yr⁻¹, while the global fertilizer input is 96 Tg N yr⁻¹ (of which 71% is synthetic fertilizers). Our estimation is close to the 12 Tg N yr⁻¹ (from synthetic fertilizer only) and 18 Tg N yr⁻¹ (11 Tg N yr⁻¹ from synthetic fertilizer and 6.5 Tg N yr⁻¹ from manure application) reported by two similar studies, Riddick et al. (2016) and Vira et al. (2020), respectively. Our estimate is higher than all three inventories of NH₃ emissions associated with synthetic fertilizers, which are 10 Tg N yr⁻¹ for CMIP6 and EDGAR and 9.1 Tg N yr⁻¹ for MASAGE. The global $R$ values are positive and lie within 0.4–0.6 across all inventories, indicating a fairly good
Table 3. Regional fertilizer-induced NH$_3$ emission totals (Tg N yr$^{-1}$) estimated by our model and reported by other inventories.

<table>
<thead>
<tr>
<th>Inventory</th>
<th>Global</th>
<th>USA</th>
<th>Europe</th>
<th>India</th>
<th>China</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAM4_CLM5_2000$^a$</td>
<td>14.2 (±0.60)</td>
<td>2.1 (±0.35)</td>
<td>0.6 (±0.07)</td>
<td>2.8 (±0.28)</td>
<td>1.2 (±0.08)</td>
</tr>
<tr>
<td>CMIP6$^b$</td>
<td>10.9 (±0.65)</td>
<td>0.9 (±0.05)</td>
<td>0.7 (±0.16)</td>
<td>1.9 (±0.15)</td>
<td>2.6 (±0.30)</td>
</tr>
<tr>
<td>EDGAR$^c$</td>
<td>10.5</td>
<td>0.7</td>
<td>0.5</td>
<td>1.6</td>
<td>3.0</td>
</tr>
<tr>
<td>MASAGE</td>
<td>9.1</td>
<td>0.5</td>
<td>0.4</td>
<td>1.7</td>
<td>2.8</td>
</tr>
</tbody>
</table>

$^a$ SDs over 20 years shown in the brackets. $^b$ SDs over 16 years are shown in the brackets (2000–2015). $^c$ Variation in 2012 in both cultural statistics and emission factors ranged from 186 % to 294 % (Crippa et al., 2018).

correlation between CLM5 and all three inventories, especially CMIP6 and MASAGE. Systematic model high biases are implied by the greater-than-unity $\beta$ values, with small NMB and MFB values ranging between +32 %–+56 % and −22 %–+32 %, respectively.

Top food-producing countries are responsible for a major portion of the fertilizer-induced NH$_3$ emission: 20 % of CLM5 global total was from India (2.8 Tg N yr$^{-1}$), 15 % from the US (2.1 Tg N yr$^{-1}$), and 8.6 % from China (1.2 Tg N yr$^{-1}$). Emission hotspots are found close to their cropping regions in the model and the inventories, but their spatial gradients are different. In India, CLM5 shows more concentrated emission sources over the northern regions, resulting in higher local emission rates than the inventories. This distribution pattern resembles India’s gradient of higher fertilization in the north and lower fertilization in the south adopted by the model. In contrast, CMIP6 estimates a more evenly distributed emission spatial pattern over India and higher emission rates over the southern regions. EDGAR and MASAGE show a spatial gradient of NH$_3$ emission decreasing from north to south. Such gradients may explain their low $R$ and high $\beta$ values against our revised CLM5. Despite the spatial mismatch, the NMB (+68 %–+74 %) and MFB (+14 %–+15 %) for the model estimation over India are relatively small.

CLM5 estimates more intense emission hotspots in the US, which are located near the “Corn Belt” of the central US and southern California. US emission rates by CLM5 are much higher than the other three inventories, as seen in the difference maps in Fig. 2, as indicated by the large $\beta$ (> 3.2) and large regional NMB. Differences in the spatial distribution of NH$_3$ emission are also observed over China. CLM5 estimates that more NH$_3$ is emitted from central and northeastern China, while the emission hotspots in CMIP6 and EDGAR are found in northeastern China, and those of MASAGE are in eastern China. Such deviation may be attributable to different fertilizer usage schedules used by CLM5 and other inventories. For example, MASAGE considers multiple types of fertilizers that can be more or less prone to NH$_3$ loss than urea (Bouwman et al., 2002) and assumes a three-stage fertilization at sowing, growth, and harvesting (Paulot et al., 2014). EDGAR also reported a high uncertainty (~ 97 %) of present-day NH$_3$ emissions in China due to incomplete information about the agricultural sector (Crippa et al., 2018).

Figure 3 shows the seasonality of NH$_3$ emission associated with artificial fertilizer in the Northern Hemisphere and Southern Hemisphere. CLM5 assumes that each crop receives a specific amount of fertilizer (as soil NH$_4^+$) applied evenly for 20 consecutive days since leaf emergence. This soil NH$_4^+$ input speeds up plant uptake, microbial immobilization, nitrification, and NH$_3$ volatilization, explaining the Northern Hemisphere peaking in emission in April and May and Southern Hemisphere peaking in October, overlapping with the regional cropping seasons. All inventories show springtime peaks in each hemisphere, but the peak of EDGAR always leads the others by a month. CMIP6 has multiple peaks (two in the Northern Hemisphere and three in the Southern Hemisphere). These deviations exist mainly because of the differences in planting schedule and duration of fertilization used by the inventories. The higher CLM5 peaks are consistent with the systematic overestimation discussed above. NH$_3$ emission returns to “background” levels when it is not in the planting seasons. EDGAR and CMIP6 have higher background levels than MASAGE because the original estimates used in this study accounted for not only synthetic fertilizer but also manure application (for both) and management (for CMIP6 only), which are not necessarily in phase with the cropping seasons (Huijmsmans et al., 2018).

We concluded our model–inventory comparison by computing the correlation of monthly NH$_3$ emission rates in each model grid cell (see Fig. 2d, f, h). CLM5 can capture a large portion of emission hotspots of CMIP6 over the US, Europe, India, China, and South America. With MASAGE, our estimate shows good agreement over mid-range emission regions, in North America, South America, Europe, and southern Africa. CLM5 differs the most from EDGAR among the three inventories. The resemblance with CMIP6 and MASAGE indicates that our NH$_3$ scheme has allowed CLM5 to produce reasonable NH$_3$ emission inputs for CAM4-chem simulations over most high- to medium-emission hotspots. It is also noteworthy that the magnitude and spatial distribution of NH$_3$ emission among inventories are also not consistent. Since environmental conditions control the rate of biological and chemical processes that release NH$_3$, processes such as urea hydrolysis and NH$_4^+/\text{NH}_3$ equilibrium can induce
Figure 2. Fertilizer-induced NH₃ emission estimated by CLM5 (synthetic and manure) and other emission inventories (synthetic only). Correlation analysis between CLM5-simulated annual-total emission and other inventories with regional breakdowns is summarized in (a). Spatial distribution of annual-total fertilizer-induced NH₃ emission simulated by [CAM4_CLM5_2000] and estimated by CMIP6, EDGAR, and MASAGE is illustrated in (b), (c), (e), and (g), respectively. Panels (d), (f), and (h) show the spatial distribution of differences in annual-total NH₃ between CLM5 and CMIP6, EDGAR, and MASAGE, correspondingly. Overlaying black dots in the difference maps indicate grid cells with a high statistically significant spatiotemporal correlation (i.e., $R^2 > 50\%$, $p < 0.05$) between CLM5 and the corresponding inventories. Color scales are saturated at respective values, and ranges of values are shown in the legend titles.
3.2 Atmospheric 

Previous studies have evaluated the reactive nitrogen processes in CESM against satellite and ground observations, e.g., depositional fluxes of NH$_3$ and NH$_4^+$ (Lamarque et al., 2013), and ground concentration of gaseous NH$_3$ (He et al., 2015). Here, we estimated the CAM4-chem-simulated annual-mean atmospheric NH$_3$ using two different sets of fertilizer-induced emissions: (1) simulated by our revised CLM5 ([CAM4_CLM5_2000]) and (2) one prescribed from CMIP6 ([CAM4_CMIP6_2000]). The sources of non-fertilizer-related NH$_3$ and other reactive gases were identical in these two cases. Figure 4 shows these results, aggregated to column total NH$_3$, alongside the 8-year annual-average IASI satellite retrievals.

Both simulations can capture the high NH$_3$ zones observed by IASI over the US, South America, and Europe, with global and regional R values > 0.5, indicating a good correlation between the modeled results and observations. However, both [CAM4_CLM5_2000] and [CAM4_CMIP6_2000] NH$_3$ are generally lower than IASI. One except is over India, in which [CAM4_CLM5_2000] estimates higher than IASI with a regional $\beta$ of 3.3. [CAM4_CLM5_2000] matches IASI better over the US (regional $\beta = 0.9$), where CLM5 estimates high emission rates. Even more significant underestimation is seen in [CAM4_CMIP6_2000] (regional $\beta = 0.5$) over the US. The magnitudes of NMB and MFB of [CAM4_CLM5_2000] are less negative than [CAM4_CMIP6_2000] in most regions, reflecting the fact that using CLM5 as NH$_3$ emission input reduces the model NH$_3$ underestimation of CAM4-chem with the default CMIP6 inventory.

Mild differences are seen in North America and northeastern China, which are both intense agricultural regions; the discrepancies are likely attributable to the mismatch in crop growth map between CLM5 and the real world. Larger differences are shown over India and western Europe, indicating the low biases in the model of emission from tropical biomass burning regions (Whitburn et al., 2017; Van Damme et al., 2018a).

We further compared the NH$_3$ burden of a run with online NH$_3$ emission but prescribed N deposition, i.e., [CAM4_CLM5_CLIM_2000], against IASI to examine whether enabling the online bidirectional exchange can improve the estimation of NH$_3$ in CLM5. The global-total NH$_3$ emission increases by 0.45 % by enabling dynamic nitrogen deposition ([CAM4_CLM5_2000]–[CAM4_CLM5_CLIM_2000]), while the regional changes are not uniform (Fig. S3). The most prominent increase is found in Asia (+0.06 Tg N yr$^{-1}$ or +0.9 % regionally), while the largest decrease is seen in Europe (−0.03 Tg N yr$^{-1}$ or −2.9 %). When compared with IASI, [CAM4_CLM5_2000] and [CAM4_CLM5_CLIM_2000] both have closer-to-one $\beta$ and closer-to-zero NMB and MFB than [CAM4_CMIP6_2000] (Fig. S4), indicating that coupling the land–atmosphere N cycle could reduce model low bias.

3.3 When 30 % more synthetic fertilizer is applied globally – a case study to reveal the importance of nitrogen deposition and aerosol–climate effect on NH$_3$ emission and grain production in a future scenario

Fertilizer use is predicted to increase by > 30 % of the 2000 level to boost grain production to meet the fast-growing food demand by 2050 (FAO, 2007). Such injection of soil nitrogen will not only enhance soil NH$_3$ emission but also alter atmospheric NH$_4^+$ formation and its subsequent climate effects and deposition, which will induce secondary impacts on crop growth and NH$_3$ re-emission. Here, we used the modified CLM5 and CAM4-chem to attribute such secondary impacts to nitrogen deposition and the aerosol–climate effect. We performed this case study by scaling up the amounts of synthetic fertilizer application by 30 % globally as input to the simulations detailed in Table 1. The application rate of manure fertilizer was assumed to be at the same level in both scenarios since increased usage would likely raise nitrogen leakage during production and transportation, which is difficult to quantify and beyond the scope of this study.

Table 4 summarizes the changes in annual-total fertilizer-induced NH$_3$ emission estimated by these simulations when the global synthetic fertilizer use rises to 130 % of the 2000 level. The total fertilization rate at the 2050 level


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Figure 4. Annual-mean atmospheric NH$_3$ estimated by CAM4-chem with online CLM5 simulation and CMIP6 emission inventory as inputs of fertilizer-induced NH$_3$ emission, which are aliased as [CAM4_CLM5_2000] and [CAM4_CMIP6_2000], respectively. Panel (a) summarizes the correlation analysis between the two simulations and the IASI satellite retrievals. Panels (b), (c), and (e) show the column NH$_3$ concentration of IASI and the two cases correspondingly. Panels (d) and (f) show concentration differences between each case and the IASI observations. Overlaying black dots in the difference maps indicate grid cells with a high statistically significant spatiotemporal correlation (i.e., $R^2 > 50\%$, $p < 0.05$) between CLM5 and IASI. Color scales are saturated at respective values, and ranges of values are shown in the legend titles.
was 117 Tg N yr$^{-1}$ (or +21% from the present-day total fertilization rate at 96.5 Tg N yr$^{-1}$, which is comparable to ~100 Tg N yr$^{-1}$ suggested by FAO, 2008). We also computed the nitrogen leakage ratio (NLR) and nitrogen use efficiency (NUE) for each case. NLR remains at ~15% for [CAM4_CLM5_2000] and [CAM4_CLM5_2050], while NUE decreases from 23% to 22%, respectively, indicating that the crops are under nitrogen surplus under this future fertilization scenario. This is also confirmed by the reduced ratio of crop uptake to fertilization from ~130% to ~115% (Table S3).

Figure 5b shows the changes in the fully coupled case, [CAM4_CLM5_2050], which estimated that global emission will rise by 3.3 Tg N yr$^{-1}$ of fertilizer-associated NH$_3$ emission than the baseline case, i.e., [CAM4_CLM5_2000]. The super-linear increase in NH$_3$ emission (+24%) relative to total fertilizer (+21%) is associated with a sub-linear rise in nitrification (+17%), crop uptake (+5.8%), and other loss processes of soil NH$_3$+). It is a result of a larger tendency of NH$_3$ volatilization compared to other loss processes during the 20 d of intensive fertilizer application, highlighting that our model modifications enabled CLM5 to simulate the dynamic competing processes of soil nitrogen. Regionally, changes in Indian and Chinese emissions are the highest, generally overlapping with the high fertilization zones (Fig. S5), totaling +1.6 Tg N yr$^{-1}$ or +24% for Asia relative to the baseline.

CLM5 assumes a harvest efficiency of 85% (Lawrence et al., 2018). [CAM4_CLM5_2050] estimated that, with nitrogen deposition and the aerosol climate effect, 243 Tg more grain (in dry matter hereinafter) is produced per year than the baseline (see Fig. 6b). Such enhancement is found dominantly over the food-producing regions over Europe (+76 Tg yr$^{-1}$ or +17%) and North America (+78 Tg yr$^{-1}$ or +17%). The grain production in Asia has divergent responses to induced fertilizers (increases in northern China and decreases in southern India). This results in a smaller Asian grain production increase of +55 Tg yr$^{-1}$ (+4%).

We evaluated the impacts of dynamic processes in our simulations by comparing the fully coupled simulation with other cases, i.e., the effects of including dynamic nitrogen deposition ($\Delta_{\text{ndep}} = \text{[CAM4_CLM5_2050]} - \text{[CAM4_CLM5_CLIM_2050]}$) and aerosol–climate interaction ($\Delta_{\text{clim}} = \text{[CAM4_CLM5_2050]} - \text{[CAM4_CLM5_NDEP_2050]}$) in the model.

As agricultural NH$_3$ is injected into the atmosphere, it rapidly neutralizes other acidic chemicals and facilitates the formation of particulate NH$_4^+$. Some of the nitrogen particles return to the surface via deposition, sequentially fuel soil NH$_3$ emission, and boost crop growth. Our simulation shows that nitrogen deposition is enhanced by 1.6 Tg N yr$^{-1}$, mostly in the US and India (Fig. S8a). It translates to an increased NH$_3$ emission by 0.47 Tg N yr$^{-1}$ globally (Fig. 7), but the enhancement is seen mostly in India. In contrast, there is a decrease in NH$_3$ emission over the US. The increase (decrease) is associated with a higher (lower) annual-mean surface temperature (Fig. S9a). In addition to directly enhancing the tendency of NH$_3$ volatilization, a warmer surface temperature also shortens the crop growth and grain filling period, resulting in lower crop nitrogen uptake (Fig. S10a) and less grain production (Fig. 8a), e.g., in India. Though the impacts of the larger nitrogen deposition in $\Delta_{\text{ndep}}$ are not evenly distributed spatially, it boosts grain production by 138 Tg N globally.

On the other hand, we expected that the sulfate aerosols induced by agricultural NH$_3$, which directly increases aerosol albedo, would reduce the amount of insolation reaching the Earth’s surface. Comparing the 2000 and 2050 fertilization levels, our fully coupled simulation estimated $-0.005$ W m$^{-2}$ in global downward radiative flux (i.e., cooling), which is virtually negligible compared to the 16-model mean total anthropogenic aerosol radiative forcing of $-0.27$ W m$^{-2}$ reported in (Myhre et al., 2013). Though the global impact is also negligible ($+0.004$ W m$^{-2}$), $\Delta_{\text{clim}}$ reveals a substantial regional cooling at the surface level (Fig. S11b) largely because there are more prognostic dusts in [CAM4_CLM5_2050] over sub-Saharan Africa than prescribed in [CAM4_CLM5_NDEP_2050]. Such a cooling effect results in lower surface temperature (Fig. S9b) and also suppression of the formation of particulate sulfate (Fig. S12b). These changes in surface temperature reduce NH$_3$ emission substantially over Africa while promoting NH$_3$ volatilization in India and North and South America, resulting in a net decrease by 0.41 Tg N yr$^{-1}$ globally. Grain production decreases by 36 Tg N yr$^{-1}$ in $\Delta_{\text{clim}}$, indicating that the warming induced by aerosol–radiation interaction partly offsets the benefit of nitrogen deposition as an extra input of soil NH$_4^+$ for crop growth and yield, though the deposition rate is increased slightly over the US (Fig. S8b).

4 Conclusions

In this study, we implemented into the land and biogeochemical model, CLM5, new mechanistic schemes to better represent fertilizer-induced NH$_3$ emission from agricultural soil. Our modifications allowed CLM5 and CAM4-chem to dynamically exchange fluxes associated with reactive nitrogen deposition and NH$_3$ emission. These new features enabled CESM2 to perform a more reliable estimation of soil NH$_3$ emission and atmospheric NH$_3$ concentration than using constant emission inventory values under dynamic climate and environmental conditions. We verified that a fully coupled simulation case, [CAM4_CLM5_2000], produced an estimation of NH$_3$ emission that agrees fairly well spatially and temporally with the emission inventories, MASAGE (Paulot et al., 2014) and CMIP6 (Hoelsey et al., 2018), especially over high-emission regions (see Fig. 2). When compared to the IASI satellite observations (Van Damme et al., 2018a), online NH$_3$ emission input in CLM5 reduces the low
Table 4. Summary of N fluxes in the simulations averaged over 20 years.

<table>
<thead>
<tr>
<th></th>
<th>Fertilization (Tg N yr(^{-1}))</th>
<th>NH(_3) Emission (Tg N yr(^{-1}))</th>
<th>NLR(^a) (%)</th>
<th>Grain N harvested (Tg N yr(^{-1}))</th>
<th>NUE(^b) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAM4_CLM5_2000</td>
<td>96.5</td>
<td>14.2</td>
<td>14.7</td>
<td>21.9</td>
<td>22.7</td>
</tr>
<tr>
<td>CAM4_CLM5_2050</td>
<td>117.0</td>
<td>17.5</td>
<td>14.9</td>
<td>25.5</td>
<td>21.8</td>
</tr>
<tr>
<td>CAM4_CLM5_CLIM_2050</td>
<td>117.0</td>
<td>17.0</td>
<td>14.5</td>
<td>24.3</td>
<td>20.8</td>
</tr>
<tr>
<td>CAM4_CLM5_NDEP_2050</td>
<td>117.0</td>
<td>17.9</td>
<td>15.3</td>
<td>25.6</td>
<td>21.9</td>
</tr>
</tbody>
</table>

\(^a\) Nitrogen leakage ratio (NLR) = NH\(_3\) emission/fertilization.
\(^b\) Nitrogen use efficiency (NUE) = grain N harvested/fertilization.

Figure 5. Changes in annual-total fertilizer-induced NH\(_3\) emission at the present-day synthetic fertilizer usage in the future scenario. Panel (a) summarizes regional changes relative to [CAM4_CLM5_2000]. Spatial distribution of the changes from [CAM4_CLM5_2000] with [CAM4_CLM5_2050] is shown in (b), with [CAM4_CLM5_CLIM_2050] in (c), and with [CAM4_CLM5_NDEP_2050] in (d). Overlaying black dots indicate grid cells with a statistically significant difference under two-sample \(t\) tests (i.e., \(p < 0.05\)) between corresponding simulations. Color scales are saturated at respective values.

Biases exhibited in CAM4-chem estimation of atmospheric NH\(_3\) using the CMIP6 NH\(_3\) emission inventory. Our modifications also enabled us to understand how NH\(_3\) emission influences aerosol formation and aerosol radiative effect and their secondary impacts on the re-emission of NH\(_3\) and grain production. Our fully coupled simulation, [CAM4_CLM5_2000], recreates the spatial distribution of the emission hotspots observed by satellite over intensive agricultural regions including China, India, Europe, and the US (see Fig. 4). We also estimate that if the synthetic fertilizer use were to increase by 30% from the 2000 level, NH\(_3\) emission would rise by 3.3 Tg N yr\(^{-1}\) globally (see Fig. 5). We further performed two simulations to highlight the importance of including a fully coupled nitrogen cycle in the model. Our results showed that lacking dynamic N deposition would underestimate NH\(_3\) emission and grain
Figure 6. Same as Fig. 5 but for annual-total grain production (in teragrams of dry matter per year).

Figure 7. Contrasting the difference in NH$_3$ emission (Tg N yr$^{-1}$). Overlaying black dots indicate grid cells with a statistically significant difference under two-sample $t$ tests (i.e., $p < 0.05$) between corresponding simulations. Only results of grid cells with croplands are shown.
production under intensified fertilization, while ignoring the aerosol–radiation interaction would lead to overestimation.

This study demonstrates a modeling approach to estimate the climatic and environmental sensitivity of NH$_3$ emission, with a focus on sources associated with manure and synthetic fertilizer only. Other primary sources of atmospheric NH$_3$ include manure management and application (47 %), ocean (16 %), and biomass burning (11 %) (e.g., Bouwman et al., 1997; Sutton et al., 2013; Paulot et al., 2014, 2015). Unlike soil emission, whereby the volatilization of NH$_3$ depends on a series of biogeochemical processes, emissions associated with manure management are typically estimated differently, e.g., collecting activity data and emission factors from factory managers and installing monitoring instruments at outlets of confined facilities such as animal factories (Bouwman et al., 1997; Paulot et al., 2014). Manure production, storage, and usage can be collected by surveying practices adopted by farmers, while its associated NH$_3$ emission can be estimated using source-specific emission factors and weather data, especially dominant factors such as air temperature, wind speed, and humidity. Fire emission directly injects the reactive nitrogen into the atmosphere, and satellite measurement is capable of capturing such short-term ammonia blooms (Van Damme et al., 2017). We did not include manure management in our study due to the high uncertainty and data insufficiency for validation. It is noteworthy that manure is attributable to up to ∼60 % of total soil NH$_3$ emission (Vira et al., 2020) and hence shall warrant further research efforts in terms of its downstream impact on ecosystems via nitrogen deposition and aerosol radiative effect.

We also incorporated a prognostic parameterization for canopy capture of the emitted NH$_3$, which is an improvement when compared to previous studies that assigned blanket reduction factors to all vegetated land types (Bouwman et al., 1997; Riddick et al., 2016; Vira et al., 2020). Despite such addition, our model still shows systematic high biases, implying room for improvement, including further calibration of the canopy capture effects against field measurements. Another source of uncertainty stems from the model’s initial soil NH$_4^+$ content, which determines the potential emission rate of NH$_3$. The overestimation by CLM5 in this study may point to the more-fertile-than-reality soil conditions in the model, highlighting the need for a more realistic soil nitrogen map compiled by field surveys to better constrain the initial conditions for the model. We also note that such field surveys, especially in underrepresented regions with low data coverage, would also be useful to infer a soil pH map that constrains the uncertainty in simulations using a constant pH, like those reported in this study.

Our schemes simplified the fate of NH$_3$ captured by the canopy and assumed that such NH$_3$ is returned to the soil and becomes immediately accessible to plants, soil microbes, and bacteria, due to limited knowledge of the consequences of the canopy capturing process. A chamber study suggested that soybean can absorb up to 20 kg N ha$^{-1}$ of NH$_3$ via leaf capturing (Hutchinson et al., 1972), which is a significant amount compared to average fertilizer use for soybean of 13–45 kg N ha$^{-1}$ in CLM5. On the other hand, concentrated NH$_3$ could damage leaf tissues if the contacting plant fails to metabolize or detoxify such a reactive gas in time (Nemitz et al., 2001). The remaining captured NH$_3$ on the leaf surface can return to the soil via throughfall, but its magnitude is difficult to measure. These unspecified processes may induce uncertainties in our simulations, especially for plant growth and soil NH$_4^+$ content. This knowledge gap points to a demand for more field experiments to investigate the impacts of these processes.

FAO projects that fertilizer use will be increased by >30 % (FAO, 2007) to boost food production to meet the fast-growing food demand by 2050. Such additional fertiliz-
izer injects mineral nitrogen into the soil that further fuels the volatilization of NH$_3$ spontaneously and hence promotes the subsequent formation of aerosol particles. This study shows the nonlinear impacts of nitrogen deposition and aerosol radiative effect on the environment. Thus, our work makes it possible to evaluate the intertwined consequences of such souring use of fertilizer on NH$_3$ emission, atmospheric aerosol composition, and the corresponding aerosol–climate effect. Our results can provide scientific information to aid stakeholders in evaluating various global and regional plans for mitigating climate change and safeguarding a sustainable environment.

**Code availability.** The modified codes of CESM2 developed in this study will be available will be available upon request.

**Data availability.** The NH$_3$ satellite data mentioned in this study were obtained from the PANGAEA repository (https://doi.org/10.1594/PANGAEA.894736) (Van Damme et al., 2018b).

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**Author contributions.** All co-authors participated in designing the experiments. KMF and MVM developed the model code. KMF performed the simulations. KMF prepared the manuscript with contributions from all co-authors.

**Competing interests.** The contact author has declared that neither they nor their co-authors have any competing interests.

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