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# Opinion: Understanding the impacts of agriculture and food systems on atmospheric chemistry is instrumental to achieving multiple Sustainable Development Goals

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**Abstract.** Agriculture and food systems play important roles shaping atmospheric chemistry and air quality, most dominantly via the release of reactive nitrogen ($N_r$) compounds, but also via agricultural burning, energy use, and cropland and pastureland expansion. In this opinion, we first succinctly review our current understanding of agricultural and food-system emissions of $N_r$ and other atmospherically relevant compounds, their fates and impacts on air quality, human health and terrestrial ecosystems, and how such emissions can be potentially mitigated through better cropland management, livestock management and whole food-system transformation. With that, we highlight important knowledge gaps that warrant more extensive research, and argue that we scientists need to provide a more detailed, process-based understanding of the impacts of agriculture and food systems on atmospheric chemistry, especially as the importance of emissions from other fossil fuel-intensive sectors is fading in the face of regulatory measures worldwide. Such knowledge is necessary to guide food-system transformation in technologically feasible, economically viable, socially inclusive, and environmentally responsible manners, and essential to help society achieve multiple Sustainable Development Goals (SDGs), especially to ensure food security for the people, protect human and ecosystem health, improve farmers' livelihood, and ultimately help communities achieve socioeconomic and environmental sustainability.

## 1 Introduction

In and after the 2023 United Nations Climate Change Conference in Dubai, United Arab Emirates (UAE), commonly known as "COP28", more than 150 nations have signed the "UAE Declaration on Sustainable Agriculture, Resilient Food Systems, and Climate Action", emphasizing the desperate need to integrate agriculture and food systems into their climate action to reach the climate goals set forth in the Paris Agreement. For the first time, agriculture has come under the spotlight of international climate negotiation, showcasing the important roles food systems play in shaping climate via contributing to a third of global anthropogenic greenhouse gas (GHG) emissions (Crippa et al., 2021). Such momentum gathered is arguably also a promising development for air quality mangers and policy makers worldwide, because agriculture and food systems are major sources of various short-lived chemical species that shape atmospheric chemistry and contribute to air pollution.

“The food we eat, the air we breathe”, the title of a recent review article (Balasubramanian et al., 2021), highlights succinctly the deep interconnection between these two things everyone needs for survival but often thinks too little about. We all need a minimum amount of nutrition from food to survive, and often a lot more for a thriving, productive and quality life. Due to population growth, rising incomes and shifting dietary habits across the world, the global food demand has increased roughly threefold from 1960 to 2010, and is projected to rise further by 40–50% by year 2050 depending on the scenario (FAO, 2018). Despite substantial gains in agricultural production to meet the rising demand due to the advancement of “Green Revolution” technologies, intensified agricultural inputs as well as cropland and pastureland expansion, undernourishment remains prevalent with a global rate of 11% in 2012; in low- and middle-income countries, the undernourishment rate can be as high as 20% in Sub-Saharan Africa and 16% in South Asia in 2012 (FAO, 2018). Even though the global food systems can indeed produce enough food for everybody, persistent poverty, inequality, uneven distribution, conflicts and socio-political instability cause people in many parts of the world to still go hungry on a daily basis. The challenge to satisfy the continuously rising food demand is further aggravated by environmental problems such as climate change and air pollution, which can severely threaten crop production and food security worldwide (Tai and Martin, 2017; Tai et al., 2014). Therefore, 193 Member States of the United Nations (UN) came together in 2015 to endorse SDG2 “Zero Hunger” as one of the 17 Sustainable Development Goals (SDGs) for the 2030 Agenda for Sustainable Development, aiming primarily to end poverty, hunger and malnutrition by year 2030, and to make the food systems more sustainable and resilient to climate change. The “UAE Declaration” mentioned above reinforced the importance of these food-centered goals for global sustainable development.

The tremendous gains in agricultural production in the past half-century have also posed severe threats to the environment, including the air we breathe. In addition to contributing to more than 30% of global GHG emissions, agricultural expansion and intensification have been a major driver of deforestation, land and water degradation, and biodiversity loss (Foley et al., 2011). The global food systems, including all the stages of pre-production, production, post-production, consumption and waste management, are estimated to account for 58% of global anthropogenic emissions of primary fine particulate matter ($PM_{2.5}$, i.e., particulate matter with a diameter of 2.5 μm or smaller), 72% of ammonia ($NH_3$), 13% of nitrogen oxides ($NO_x = NO + NO_2$), 9% of sulfur dioxide ($SO_2$), and 19% of non-methane volatile organic compounds (VOCs) (Balasubramanian et al., 2021). Such emissions are estimated to be responsible for 22% of global mortality arising from poor air quality and 1.4% of global crop production losses in year 2018 (Crippa et al., 2022b). Moreover, reactive nitrogen ($N_r$) compounds of agricultural origins including $NH_3$, $NO_x$, nitrous acid (HONO) and their reaction products can readily be deposited back onto the land surface, causing various effects on terrestrial ecosystems, including more serious nutrient leaching and soil acidification (Guo et al., 2010; Lu et al., 2011). They may also enhance plant growth and soil carbon storage especially where nitrogen is a limiting nutrient (Liu et al., 2021b; Thomas et al., 2010; Zhao et al., 2017), but such enhancements generally favor the more competitive plant species and may ultimately reduce species diversity of plant communities (Bobbink et al.,

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2010). All these findings highlight the importance of agriculture and food systems in shaping atmospheric chemistry, air pollution, and the associated public health and ecosystem impacts.

Globally, air pollution causes about 6.7 million premature deaths annually (Institute, 2020), representing a major public health threat. The nitrogen load released by anthropogenic activities has also exceeded the so-called planetary boundary, meaning that human disturbances of the nitrogen cycle are destabilizing natural ecosystems to a possibly irreversible extent (Richardson et al., 2023). In a recent Nature Portfolio journals' collection on "Air Pollution and Global Solutions", out of 34 featured articles, only five directly address food system emissions or food security issues, and all of them emphasize substantial knowledge gaps in understanding agricultural and food-system impacts on the atmospheric environment. Mitigating agricultural emissions will be even more important in the future as global air quality control efforts targeting mostly sources from the energy and transportation sectors have already substantially reduced $NO_x$ and $SO_2$ emissions in many parts of the world. But how can we do that without compromising the needs of people to be food-secured and nourished? Here we argue that, to protect people and ecosystems from the harmful effects of air pollution worldwide but especially in developing regions, society needs to lay larger emphasis than now on reforming the food systems and mitigate their emissions of various pollutants, while ensuring food security for the people and livelihood of the farmers. To support that, scientists need to provide a more solid understanding of how different parts and stages of the food systems emit different compounds, how these compounds are transported, transformed and deposited back onto the surface, and how the food systems can be modified in technologically feasible, economically viable and socially equitable manners to abate emissions.

## 2 How agriculture and food systems shape atmospheric chemistry and air pollution

### 2.1 Emissions of reactive nitrogen

Nitrogen is predominantly found in its inert form, dinitrogen ($N_2$), in nature (Galloway et al., 2013). Only a small fraction of nitrogen is reactive as $N_r$ and readily available to organisms. The advent of the Haber-Bosch process has revolutionized the way humans utilize nitrogen, allowing for the conversion of $N_2$ into $NH_3$ for fertilizer and other uses. Since then, the use of nitrogen-based fertilizers in agriculture has substantially increased, rising from 11.4 Tg N in 1961 to 108 Tg N in 2021 (FAO, 2024). This intensive and excessive use of fertilizers often surpasses crop nutrient demands, whereby only about half of the applied nitrogen is harvested in crops (Zhang et al., 2015). In livestock systems, nitrogen use efficiency (NUE) is even lower, with only 10% of the nitrogen in feed being converted to livestock products (Uwizeye et al., 2020). Consequently, in both cropland and livestock systems, a significant portion of the added nitrogen is lost to the environment after undergoing various biogeochemical processes primarily mediated by microbes, leading to the emissions of many $N_r$ compounds, including $NH_3$, $NO_x$, and HONO, along with the potent greenhouse gas nitrous oxide ($N_2O$), into the atmosphere. When considering the entire food systems beyond agricultural production, $N_r$ emissions can be even higher. Food-system

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energy use, encompassing activities such as fertilizer production, transportation, and processing, along with land use change driven by agricultural expansion, also contributes to substantial $NH_3$ and $NO_x$ emissions (Balasubramanian et al., 2021).

Emission estimation plays a crucial role in investigating the impact of agriculture and food systems on atmospheric chemistry. Agricultural $N_r$ emissions are typically estimated using two primary approaches: bottom-up and top-down methods. The bottom-up approach can be further categorized into multiplicative schemes based on emission factors (EFs) and mechanistic process-based models. The EF approach estimates agricultural emissions as multiplicative functions of agricultural activities (e.g., fertilizer use, livestock population) and their corresponding EFs under "standard" conditions (Bouwman et al., 1997; Misselbrook et al., 2000). Since agricultural emissions are influenced by multiple factors, including meteorological conditions, soil properties, and farming practices, the most advanced EF methods refine their EFs by localizing these factors as much as possible. For livestock systems, refined EFs can be developed for each stage along the manure management chain (e.g., housing, storage, spreading) to achieve more accurate estimation (Huang et al., 2012). Process-based methods that rely on agroecosystem models is the most advanced bottom-up approach to estimate emissions from croplands. Agroecosystem models, such as the DayCent and Denitrification-Decomposition (DNDC) models, explicitly track the transport, biogeochemistry and fates of $N_r$ in the soil in a mechanistic manner (Del Grosso et al., 2009; Li et al., 2000; Vira et al., 2020), and can reflect the nonlinear responses of emissions to meteorological conditions, soil properties, and farming practices.

Top-down inversion methods have also been developed to refine emission estimates. This approach uses *a priori* bottom-up estimates (e.g., from EFs) and then assimilates observational data via air quality modeling to create *a posteriori* estimates, aiming to minimize discrepancies between observations and estimates. Satellite-derived observations of atmospheric $NH_3$ and $NO_x$ column concentrations have widely been used to improve agricultural emission estimates, especially in regions lacking field measurements. More recently, the launch of geostationary satellites with high spatiotemporal resolutions (e.g., TEMPO, GEMS) is expected to further enhance the accuracy of agricultural emission estimates over North America and Asia (Kim et al., 2020; Zoogman et al., 2017).

Within the air quality research community, the bottom-up approach is the most commonly used for estimating agricultural emissions. However, the derived emission estimates often exhibit high uncertainties, with variations of up to a factor of two to three, and, in some cases, even an order of magnitude different from observations (Table 1). The refinement and localization of EFs relies on extensive field measurements, which renders EF estimates relatively more accurate in heavily researched regions such as the US, Europe, and China (Ma et al., 2021; Vigan et al., 2019). However, for developing regions such as Latin America, Africa, and South Asia, sporadic field measurements are not sufficient for EF refinement and localization, where emission estimates often rely on general EFs obtained from more developed regions, lack accurate activity data (e.g., fertilizer input, manure use), and thus suffer significant uncertainties. This also contributes to the substantial differences between different global inventories. Another limitation is the relatively coarse temporal resolution (often on a monthly scale), which makes it difficult to capture the influence of abrupt increases in agricultural $NH_3$ emissions on atmospheric chemistry, as $NH_3$ typically peaks within several days after fertilizer application (Nelson et al., 2019).

Process-based models, often favored by the agroecosystem research community for analysis on field scales (~100 ha) and daily timescales, face challenges in regional and larger-scale applications due to their high demand for input data. Nevertheless, recent studies have successfully integrated process-based models with air quality models to estimate $N_r$ emissions and their impacts on the atmosphere (Balasubramanian et al., 2020; Luo et al., 2022a), leading to enhanced spatiotemporal accuracy. Despite these improvements, most agroecosystem models are parameter-intensive, requiring field measurements to constrain the default parameter values. It remains questionable whether agroecosystem models can be effectively applied on larger, pan-regional scales, as even in the US and China field measurements are insufficient to cover all types of cropping systems. Furthermore, some recent studies have indicated that agricultural emissions may be substantial during non-growing seasons (Yang et al., 2022), may stem from some neglected nitrogen-cycle processes (Wrage-Mönnig et al., 2018), and may be stimulated by dry-wetting and freeze-thawing events (Del Grosso et al., 2022). A further refinement in nitrogen-cycle representation within agroecosystem models is much warranted.

Table 1. Global estimates of $NH_3$ and $NO_x$ emissions (Tg N yr$^{-1}$).

| Sources | Method | Base year | Agricultural $NH_3$ | Total $NH_3$ | Agricultural $NO_x$ | Total $NO_x$ |
|---|---|---|---|---|---|---|
| EDGAR (Crippa et al., 2018) | Bottom-up | 2018 | 38.2 | 43.7 | 1.9 | 36.5 |
| CEDS (McDuffie et al., 2020) | Bottom-up | 2017 | 39.2 | 51.6 | 2.3 | 37.7 |
| HTAP (Crippa et al., 2023) | Bottom-up | 2018 | 42.5 | 48.5 | 1.7 | 35.6 |
| Fowler et al. (2013) | Bottom-up | 2010 | 59.9 | 69 | | |
| Yang et al. (2023) | Bottom-up | 2018 | 60 | | | |
| Beusen et al. (2008) | Bottom-up | 2000 | 26.4 | | | |
| Huang et al. (2017) | Bottom-up | 2014 | | | | 39.2 |
| Luo et al. (2022b) (EDGAR as prior) | Top-down | 2018 | | 71.9 | | |
| Miyazaki et al. (2017) (EDGAR as prior) | Top-down | 2014 | | | | 47.5 |

## 2.2 Other contributions

In addition to $N_r$, agriculture and food systems are also major sources of a range of atmospherically relevant compounds, including primary particulate matter (PM), carbon monoxide (CO), methane ($CH_4$), $SO_2$, and VOCs (Crippa et al., 2022a), much of which can be closely linked to agricultural burning practices (e.g., for managing crop residues, land clearance). About 11% ($83 \pm 14$ Mha $yr^{-1}$) of total burned area globally is attributed to crop residual management, primarily occurring in South and Southeast Asia, and Sub-Sahara Africa (Chen et al., 2023). In developed countries such as the US and European nations, agricultural burning is heavily regulated, with a focus on promoting alternative methods for managing crop residues and allowing controlled burning under specific meteorological conditions to minimize environmental impacts (Hall et al., 2021; Nematian et al., 2023). In contrast, agricultural burning remains widespread in developing regions, often due to the limited time between cropping seasons and high costs of alternative management methods (Lin and Begho, 2022). Additionally, deforestation accounts for $3.8 \pm 1.2$ Mha $yr^{-1}$ of the global burned area, which is frequently observed in South America and sub-Sahara Africa (Chen et al., 2023), and is largely driven by the expansion of pasturelands and croplands (e.g., soybean and palm tree cultivation).

Agricultural burning causes significant emissions of air pollutants, e.g., representing the largest source of primary PM from agriculture and food systems (Balasubramanian et al., 2021). The estimation of agricultural fire emissions often relies on satellite-derived datasets, such as the Global Fire Emissions Database (GFED) based on the 500-m MODIS burned area product (van der Werf et al., 2017), which poses challenges for detecting small fires such as crop residual burning. Although the "small fire boost" method has been applied in GFED v4.1s to enhance the identification of small fires, the improvement of accuracy is limited (Zhang et al., 2018). It is thus important to devote more attention to the characterization of air pollutants from agricultural burning, not only because of their large emissions, but also because they are important considerations in formulating equitable emission reduction policy in developing regions, where the poorer agricultural populations are disproportionately affected. Finally, other practices in the food systems, including manure management and use of machinery and vehicles, contribute to the release of VOCs and $SO_2$, responsible for 16% and 12% of the total global emissions of VOCs and $SO_2$, respectively (Crippa et al., 2023). However, food-system energy use is rarely accounted for, which also limits the assessment of the impacts of the entire food systems on the atmosphere.

## 2.3 Effects on atmospheric chemistry and ecosystems

### 2.3.1 Impacts of agricultural $NH_3$ emissions on $PM_{2.5}$ pollution and human health

Agricultural $NH_3$ emissions significantly contribute to $PM_{2.5}$ pollution. $NH_3$, the most abundant alkaline gas in the atmosphere, neutralizes sulfuric acid ($H_2SO_4$) to form ammonium sulfate and, when in excess, reacts with nitric acid ($HNO_3$) to form ammonium nitrate. These compounds, often termed secondary inorganic aerosols, are key components of $PM_{2.5}$, which is a major health risk worldwide, responsible for millions of premature deaths annually (Lelieveld et al., 2015). Traditional $PM_{2.5}$ control policies have targeted mainly combustion-related emissions of $SO_2$ and $NO_x$, which have already led to significant improvements in $PM_{2.5}$ air quality in regions such as the US, Europe and, more recently, China, but ongoing efforts are still essential for further air quality improvements especially in developing countries, but even in cleaner regions such as the US that still witnesses thousands of deaths every year (Thakrar et al., 2020; Tschofen et al., 2019). More importantly, $NH_3$, another important precursor of $PM_{2.5}$, has historically received much less attention, and its primary source, agriculture, has always been less regulated than other sectors. However, agriculture $NH_3$ is an increasingly important contributor to $PM_{2.5}$ globally, accounting for approximately 34% of annual $PM_{2.5}$ concentrations in Europe, 23% in the western US, 36% in the eastern US, and 31–33% in China (Bauer et al., 2016; Han et al., 2020; Pozzer et al., 2017). The dominant influence of $NH_3$ on $PM_{2.5}$ is via affecting ammonium nitrate formation, especially during winter (Han et al., 2020; Pozzer et al., 2017).

Due to the strong nonlinearity of inorganic aerosol chemistry, the sensitivity of $PM_{2.5}$ to $NH_3$ emissions varies widely across different regions, mostly depending on the regional atmospheric conditions, seasonal meteorological conditions, and the intensity of mitigation efforts (Thunis et al., 2021). The $PM_{2.5}$ burden in China shows a higher sensitivity to agricultural $NH_3$ emissions compared to combustion-related $NO_x$ emissions (Bauer et al., 2016). For the Beijing-Tianjin-Hebei region in particular, a joint control of $NH_3$, $NO_x$, and $SO_2$ is essential, especially as $NO_x$ and $SO_2$ levels remain high (Fu et al., 2017; Liu et al., 2021c). In the western US, $PM_{2.5}$ sensitivity to $NH_3$ reductions is pronounced with reduction intensities of 40% to 60% (Bauer et al., 2016). In the eastern US and India, $PM_{2.5}$ shows similar sensitivities to both combustion $NO_x$ and agricultural $NH_3$, while Europe demonstrates greater sensitivity to $NO_x$ than $NH_3$ emissions, particularly in western Europe, but a joint control strategy is preferred in eastern Europe (Bauer et al., 2016; Liu et al., 2023).

Furthermore, some studies have directly examined the health damage related to air quality associated with crop production processes, highlighting that animal-based foods contribute to higher PM pollution and subsequent health damage than plant-based foods, as livestock management results in greater $NH_3$ emissions compared to fertilizer applications on croplands (Domingo et al., 2021). Health effects induced by fertilizer use are more significant in densely populated regions close to the farms (Hill et al., 2019).

In general, despite lower $NH_3$ emissions at lower temperatures, the effects of mitigating agricultural $NH_3$ are stronger in winter, when lower temperatures favor the formation of ammonium nitrate (Pozzer et al., 2017). $PM_{2.5}$ formation is sensitive to reductions in $NO_x$ emissions in $NH_3$-rich environments and becomes more sensitive to $NH_3$ in environments with lower $NH_3$ levels (Ansari and Pandis, 1998; Holt et al., 2015; Liu et al., 2023). The relative effectiveness of controlling agricultural $NH_3$ emissions may diminish when substantial amounts of $NO_x$ and $SO_2$ are under control, as $NH_3$ is more likely to remain in the gas phase rather than contributing to $PM_{2.5}$ formation (Fu et al., 2017). Controlling agricultural emissions benefits not only rural areas but also downwind urban regions especially for poorer populations near the farms (Hill et al., 2019). From a policy-making perspective, $NH_3$ abatement may be even more cost-effective than $NO_x$ for controlling $PM_{2.5}$ pollution (Gu et al., 2021; Pinder et al., 2007).

Uncertainties and limitations still abound in our understanding of the impacts of agricultural $NH_3$ on $PM_{2.5}$ formation. A major source of uncertainty stems from the nonlinear and high sensitivity of $PM_{2.5}$ to the nitrate-ammonium ratio, which may be prone to large errors due to uncertainties in both $NO_x$ and $NH_3$ emission estimates. Consequently, even within the same region, the response of $PM_{2.5}$ to agricultural $NH_3$ emissions can vary between studies. For instance, one study suggested that reducing agricultural $NH_3$ emissions by 40% could decrease secondary inorganic PM in winter haze events by 21% (Han et al., 2020), while another found that a reduction of over 50% was needed to have similar effects in the same region (Guo et al., 2018; Song et al., 2019). Another source of uncertainty lies in the source apportionment methods used to estimate the contribution of agricultural emissions to $PM_{2.5}$. Source apportionment studies relying on air quality models use either the brute force method (BFM, also known as the zero-out method) or the tagged species-based approach. A recent study applying both methods to estimate the impact of agricultural $NH_3$ emissions found that the tagged species-based method attributes a 16% contribution to $PM_{2.5}$, whereas estimates from BFM reach up to 33% (Han et al., 2020). While BFM is effective for sensitivity analysis in examining the responses of $PM_{2.5}$ to reductions in precursor emissions, the tagged species-based method is more suitable for source contribution studies owing to the nonlinear nature of $PM_{2.5}$ to its precursors.

From the perspective of $PM_{2.5}$ pollution control, region-specific investigation for the responses of $PM_{2.5}$ to precursor reductions with higher spatial resolutions is strongly preferred to larger-scale (e.g., national) analysis, and such investigation should be updated periodically as emission inventories are revised. There is also a lack of studies with high temporal resolutions, such as weekly or daily, which is particularly important because $NH_3$ emissions typically peak about one week after fertilizer application and such temporal details may influence episodic $PM_{2.5}$ pollution but are lost if monthly emissions are used (Nelson et al., 2019). A more detailed spatiotemporal analysis shall refine our understanding of the specific locations and periods most influenced by agricultural activities, possibly enabling more effective pollution mitigation strategies.

### 2.3.2 Impacts of agricultural burning on air quality and human health

Agricultural burning significantly shapes atmospheric chemistry, particularly in South Asia and Africa, leading to the formation of harmful air pollutants including $PM_{2.5}$ and ozone ($O_3$), mostly via substantial emissions of primary PM, CO, $CH_4$, and VOCs. Once these pollutants are released into the atmosphere, they can affect not only local areas but also be transported to downwind regions. The pollution-related health burdens from agricultural burning disproportionately affect low-income individuals in rural areas or near the burning sites (Reddington et al., 2021). $PM_{2.5}$ emissions from agricultural fires are often considered more harmful than those from other sources due to their composition and the potential for long-range transport (Lin and Begho, 2022). Specifically, in Delhi, India, agricultural burning is shown to be responsible to approximately 7% to 78% of the enhanced $PM_{2.5}$ concentrations (Cusworth et al., 2018). In Southeast Asia, agricultural and deforestation fires are estimated to account for about 40% to 70% of annual $PM_{2.5}$ concentrations in northern Thailand, Myanmar, Cambodia, and Laos, resulting in ~59,000 annual premature deaths (Reddington et al., 2021). These fires also contribute to $O_3$ pollution, accounting for 5% of the average daily maximum 8-hour $O_3$ concentration and causing ~3,800 annual premature deaths (Reddington et al., 2021). Agricultural burning is a major source of $PM_{2.5}$ pollution in South Asia, contributing to its status as one of the most polluted regions globally (Lan et al., 2022; Lin and Begho, 2022). In Africa, agricultural burning contributes to 22% of the annual average $PM_{2.5}$, leading to 106,000 premature deaths, though another study estimated a lower number of ~43,000 deaths (Gordon et al., 2023).

Agricultural burning in South Asia, Southeast Asia and Africa is challenging to detect and characterize quantitatively due to its small scales but large numbers, and estimates based on satellite observations suffer from inadequate resolutions for such detection, leading to significant uncertainties in emission estimates (Korontzi et al., 2006). In addition, the widely-use bottom-up methods for emission inventories heavily rely on crop-type specific EFs, but often use fixed factors for different crops, further increasing uncertainties (Zhang et al., 2020a). The lack of air monitoring networks in these regions further complicates the linkage between fire activities and pollution-related health damage. More field measurements to identify important emitted species and track their chemical transformation for different cropping systems or crop types, especially in developing regions, are very much warranted.

### 2.3.3 Impacts of agricultural $NO_x$ and HONO emissions on air quality

Agricultural emissions of $NO_x$ from fertilized soils, historically overlooked in $O_3$ research, are now acknowledged for their impacts on $O_3$ pollution in agriculturally intensive regions. Recent studies in rural areas with intensive agricultural activities have shown that $NO_x$ emissions from fertilized soils significantly enhance ozone formation (Romer et al., 2018). For example, in California, agricultural NO emissions account for approximately 40% of the total $NO_x$ emissions and contribute to ~23% to $O_3$ formation (Sha et al., 2021). In China, agricultural soil $NO_x$ emissions may also account for ~40% of $O_3$ nonattainment in some regions of China (Huang et al., 2023). Similarly, a US study suggested that in low $NO_x$ environments, controlling agricultural soil $NO_x$ emissions is more effective for $O_3$ reduction than the same level of control on biogenic VOCs (Geddes et al., 2022). Beyond $NO_x$-limited regions, agricultural $NO_x$ emissions are also influential in some $NO_x$-saturated or transition-regime areas where agricultural $NO_x$ emissions are on a par with combustion-related $NO_x$ emissions; there controlling agricultural $NO_x$ emissions can be more effective than other anthropogenic sources (Lu et al., 2021b).

As the mitigation of anthropogenic non-agricultural $NO_x$ emissions become more successful, many regions may eventually transition to being $NO_x$-limited, suggesting that the importance of agricultural $NO_x$ to $O_3$ control is expected to rise. A better understanding of the impacts of agricultural $NO_x$ on $O_3$ chemistry requires more accurate emission estimation and more precise source apportionment analyses. Previous studies using air quality models have either neglected soil $NO_x$ emissions or relied on simplified EF-based methods that fail to capture spatiotemporal variability of emissions. Recent advancements in mechanistic parameterization schemes, such as the Berkeley-Dalhousie Soil $NO_x$ Parameterization (BDSNP) scheme (Hudman et al., 2012), have improved our understanding of soil $NO_x$ and $O_3$ chemistry, but more field measurements from poorly researched regions are much needed to enhance regionalized applicability.

Finally, beyond $NH_3$ and $NO_x$, agricultural emissions of HONO are also important for atmospheric chemistry, mostly because of its photolysis product, hydroxyl radical (OH), the primary oxidant in the troposphere, which is heavily involved in $PM_{2.5}$ and $O_3$ chemistry (Oswald et al., 2013). A recent modeling study revealed that HONO emissions from fertilized agricultural soils could increase average daytime $O_3$ and daily particulate nitrate concentrations across the North China Plain by 8% and 47%, respectively (Wang et al., 2021), and by 4.6% and 14%, respectively, even in non-growing seasons (Wang et al., 2023). However, more accurate parameterization for HONO emissions is needed to improve the estimates.

### 2.3.4 Impacts of nitrogen deposition on terrestrial ecosystems

The $N_r$ compounds of agricultural origins often undergo transport and chemical transformation, and are eventually deposited back onto the surface of terrestrial and aquatic ecosystems, resulting in increased nitrification, nutrient leaching, soil acidification (Guo et al., 2010), and biodiversity loss (Simkin et al., 2016), while also possibly enhancing forest growth, carbon storage (Liu et al., 2022; Lu et al., 2021a; Quinn Thomas et al., 2010), and marine productivity (Jickells and Moore, 2015). Due to historically more stringent emission controls on combustion $NO_x$ than agricultural $NH_3$ emissions, $N_r$ deposition patterns are shifting from being nitrate-dominated to ammonium-dominated, a trend observed in the US and China, and expected in Europe (Chen et al., 2020; Li et al., 2016; Liu et al., 2020; Tan et al., 2020). Although the deposition of oxidized $N_r$ compounds has decreased, increased deposition of reduced $N_r$ compounds from agricultural $NH_3$ emissions, particularly in regions with intensive fertilizer use or near animal feeding operations, may offset such reduction (Chen et al., 2020; Tan et al., 2020). Control measures for $N_r$ deposition show varied effectiveness between oxidized and reduced forms. Each unit of $NO_x$ control can achieve 80–120% reductions in oxidized deposition, whereas each unit of $NH_3$ control can only achieve 60–80% reductions in reduced-form $N_r$ deposition (Tan et al., 2020).

A recent paper has systematically reviewed the quantification methods for nitrogen deposition and summarized the major uncertainties (Zhang et al., 2021a). Global monitoring networks for nitrogen deposition have been established, especially in the US, Europe, and East Asia, offering relatively accurate data for wet deposition. However, significant challenges remain in measuring dry deposition due to the need for highly advanced instruments and analysis methods. Further technological innovations in measurements are warranted. The spatial distribution of observation sites also needs to be optimized to cover more representative locations and reduce sampling time to prevent sample losses. In addition, integration of Earth system models and satellite retrievals has enhanced our understanding of the spatial distribution and temporal variations of $N_r$ deposition and their ecosystem effects (Liu et al., 2017; Zhao et al., 2017a). Nevertheless, model estimation of $N_r$ deposition still has substantial limitations that arise from poor representation of the bidirectional exchange of $NH_3$, inaccurate dry deposition velocities, poor representation of organic nitrogen compounds, and uncertainties in $N_r$ emission estimates. The utility of satellite observations is also constrained by their spatiotemporal coverage and retrieval methods. To enhance our current understanding of $N_r$ deposition, a comprehensive framework that integrates these methods, supported by international collaboration, is strongly encouraged.

## 3 How agriculture and food systems can be transformed to mitigate emissions

### 3.1 Cropland systems

Nitrogen management in croplands is a crucial challenge of the 21st century, as we need to balance food production with pollution mitigation (Davidson et al., 2015; Houlton et al., 2019). To that end, NUE is a vital metric. The current global average NUE stands at ~0.4, yet we need to increase it to ~0.7 by 2050 to meet the growing global food demand while minimizing environmental degradation, in line with the UN SDGs (Alexandratos and Bruinsma, 2012; Zhang et al., 2015). NUE varies globally, with higher values in high-income countries such as the US and Canada (0.68) as well as Europe (0.52), and lower in middle-income countries such as China (0.25) and India (0.30) (Zhang et al., 2015). In low-income regions, such as Sub-Saharan Africa (0.72), NUE is initially high due to low fertilizer use but is expected to decrease as fertilizer use increases (Zhang et al., 2015).

Agricultural $N_r$ emissions are closely tied to farming practices aimed at boosting crop productivity. The goal of nitrogen management is to match nutrient supply with crop demands effectively. Therefore, choosing appropriate farming practices, particularly adhering to the principles of "4R nutrient stewardship" (i.e., applying fertilizer with the right source, right rate, right time, and right place) (Bruulsema et al., 2009), has shown potential in mitigating $N_r$ emissions while maintaining or even enhancing crop productivity (Gu et al., 2023). Additionally, using enhanced-efficiency fertilizers (Akiyama et al., 2009; Qiao et al., 2015) such as slow-release and controlled-release fertilizers, fertilizers containing nitrification inhibitors (NIs) and/or urease inhibitors (UIs), adopting efficient irrigation practices (Holcomb et al., 2011), and incorporating biochar amendments (Luo et al., 2023), can also help reduce $N_r$ emissions (summarized in Table 2).

Table 2. Effects of different management strategies on agricultural nitrogen emissions, as adapted from (Gu et al., 2023).

| Strategies | | $NH_3$ | $NO_x$ |
|---|---|---|---|
| Fertilizer management | Rate | –42% | –26% |
| | Type | –66% | –37% |
| | Time | +17% | –74% |
| | Placement | –72% | / |
| Irrigation management | | –36% | –93% |
| Biochar amendment | | +38% | –19% |
| Enhanced-efficiency fertilizers | | –70% | –46% |

To mitigate agricultural burning emissions. eco-friendly crop residue management options have been explored. In-situ methods such as reduced tillage hold much promise, yet they can also stimulate $N_r$ emissions under certain conditions (Lin and Begho, 2022). Another approach involves converting crop residues into biochar or harnessing crop residues for renewable energy sources; however, these methods come with additional costs and technological requirements, making it less feasible in some developing countries (Lin and Begho, 2022). Effective crop residue management in South Asia and Africa remains a complex challenge that requires addressing various hurdles.

Cropland nitrogen management, while extensively researched, lacks a one-size-fits-all solution due to the diversity of cropping systems. The impact of various practices on $N_r$ emissions varies significantly across regions and species. Managing $N_r$ emissions often leads to trade-offs among different $N_r$ species from fertilized soils (Gu et al., 2023; Pan et al., 2022; Qiao et al., 2015). Additionally, management strategies should account for other $N_r$ losses, such as surface runoff, leaching, and potential changes in crop yield. Customized, region-specific, and even farm-specific evaluation is essential for harmonizing agricultural and environmental goals. Additionally, future climate change is likely to increase the occurrence of extreme weather events, imposing additional demands on cropland systems for resilience. This will further complicate nitrogen management, necessitating adaptive strategies to maintain agricultural productivity while managing $N_r$ emissions effectively in the face of these evolving environmental challenges.

### 3.2 Livestock systems

Sustainable livestock management serves as another crucial pillar in achieving low-emission agriculture and food systems, with the pathway to this goal fundamentally rooted in the optimization of resource use efficiency. Guiding by this principle, a series of measures about livestock management (e.g., sustainable intensification, animal health, and recoupling between cropping and livestock systems) and manure management (technological options at feeding, housing, storage stages) have been taken. Current estimates of emission reductions from these measures are limited, leaving great uncertainties in the outcomes of currently reported mitigation measures such as those listed in Table 3. Herd size can also help improve resource use efficiency (FAO, 2023). Industrial and intensive livestock farms can produce animal products more efficiently and have lower emissions compared to small farms (Herrero et al., 2013), but focusing solely on improving resource use efficiency may compromise other aspects, such as causing local nutrient overload (Bai et al., 2022) and harming animal welfare (FAO, 2023). Furthermore, increasing industrial livestock farms disrupts nutrient recycling between livestock and croplands, inducing nutrient imbalances (Jin et al., 2020). It is important to note that a single measure may effectively control certain air pollutants while potentially increasing other air pollutants or greenhouse gas emissions. For example, anaerobic digestion, a biological process where bacteria degrade organic matter without oxygen, produces biogas for renewable energy, which can supply on-farm energy needs with lower emissions, but may raise the $NH_3$ emissions of the digestate (Yan et al., 2024). Overall, there are a number of abatement options, but more knowledge about their effectiveness, cost-effectiveness performance, and trade-offs is required to underpin the development of abatement measures or design of sustainable livestock systems.

Table 3. $NH_3$ emission abatement efficiency for different manure management options, as adapted from Hou et al. (2015) and Zhang et al. (2020b).

| Stage | Measure | Reduction in $NH_3$ emissions |
|---|---|---|
| Feeding | Low-crude protein feeding | 24–65% |
| | Dietary additives | 33–45% |
| Housing | Floor adaption | 10–50% |
| | Frequent manure removal | 25–30% |
| | Rapid manure drying | 70–90% |

| | | |
|---|---|---|
| Storage | Solid-liquid separation | 20–30% |
| | Manure surface covers | 50–88% |
| | Acidification by additives | 18–70% |
| | Composting<br>(aeration, turning, compaction) | 55–97% |

### 3.3 Whole food systems

The entire food systems include not only on-farm production but also upstream and downstream stages such as agricultural input (e.g., fertilizer, pesticide) production, food processing, distribution, storage, retail and consumption. Food loss typically occurs in the pre-production and production stages due to inadequate management and technology, whereas food waste happens during retail and consumption. About one third of the total food production (~1.3 billion tonnes) is discarded as food loss and waste (FLW) (Shafiee-Jood and Cai, 2016). Efforts to reduce FLW have shown promising results in mitigating $NH_3$ emissions and $PM_{2.5}$ pollution, with estimates suggesting a potential reduction of up to 11.5 Tg in $NH_3$ emissions and a decrease of about 5 $\mu g\ m^{-3}$ in $PM_{2.5}$ levels worldwide (Guo et al., 2023). In addition, the widespread dietary shifts from plant-based to meat-intensive diets are the key driver for the globally increasing food demand, and meat-intensive diets are not only linked to increased risks of cardiovascular diseases, cancers, and type-2 diabetes, but also pose severe environmental threats (GBD, 2019; Liu et al., 2021a). For instance, during 1980–2010 in China, dietary change alone could raise $NH_3$ emissions by 63% and annual mean $PM_{2.5}$ by up to ~10 $\mu g\ m^{-3}$ (Liu et al., 2021a). The study further suggested that adopting more sustainable, healthier, less meat-intensive diets could decrease annual mean $PM_{2.5}$ by 2–6 $\mu g\ m^{-3}$ in China. Likewise, a worldwide shift to plant-based diets could cut agricultural emissions significantly, by 44–86%, especially in regions with extensive livestock production (Springmann et al., 2023). Such dietary changes are expected to lower $PM_{2.5}$ and $O_3$ pollution by 3–7% and 2–4%, respectively, reduce premature mortality by 3–6%, and enhance economic output by 0.5–1.1%. Overall, reducing FLW and dietary changes can have multiple benefits for people, prosperity and the planet; specifically concerning atmospheric chemistry, they help mitigate pollutant emissions throughout the whole food supply chain by reducing the overall food demand. Currently, agricultural emission abatement is usually more focused on on-farm production and the food supply. Stronger emphasis on whole food-system transformation and formulating integrated policies that target both the demand and supply sides of food and agriculture is much warranted.

## 4 How the science of agriculture-environment interactions contributes to sustainable development

Sustainable development is development that aims to meet the needs of the present generation without compromising the ability of future generations to meet their own needs (Brundtland, 1987). It is a holistic approach that emphasizes that the “needs” of every one but especially the poor and disadvantaged should be prioritized, and that there are “limitations” to the

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environment's ability to meet such needs. The goals of sustainable development are thus to seek economic prosperity for the people in a way that is socially inclusive and environmentally responsible; that is, economy, society and environment are equally important considerations when pursuing long-term human development. The 17 UN SDGs adopted in 2015 provide a framework for governments, businesses and civil society to work toward sustainable development across all sectors, of which agriculture and food systems are among the most important, as most obviously indicated by SDG2 "Zero Hunger", which aims to end hunger, achieve food security, enhance nutrition, and promote sustainable and climate-resilient food systems. However, the SDGs are not meant to be standalone objectives, but are interconnected and need to be considered holistically to achieve various objectives, and here we argue that a better understanding of agricultural and food-system contributions to atmospheric chemistry is indeed crucial to help stakeholders achieve SDG2 in synchrony with other SDGs, especially SDG3 "Good Healthy and Well-being", SDG13 "Climate Action" and SDG15 "Life on Land", but also various others more indirectly.

The previous sections have highlighted how agriculture and food systems are important sources of $N_r$ and other air quality-relevant compounds, and thus contribute substantially to $PM_{2.5}$ pollution, and to $O_3$ pollution to a lesser but increasingly important extent. These pollutants are shown to cause some of the most fatal non-communicable diseases such as cardiovascular diseases, cancers and respiratory diseases, taking significant tolls on human health and well-being worldwide. Therefore, better understanding and quantification of these sources are crucial to achieving SDG3 "Good Health and Well-being", which aims to ensure healthy lives and promote well-being for all at all ages. This is particularly important now as so many emission control efforts have already been in place for decades to reduce non-agricultural sources of air pollutants, such as combustion-derived $NO_x$ and $SO_2$ from the energy and transportation sectors, but relatively little has been done to mitigate agricultural emissions, and we foresee the increasing dominance of agricultural $N_r$ as well as unmitigated agricultural burning in shaping future aerosol chemistry. To that end, as reviewed above, scientists need specifically to 1) conduct more field measurements in representative agricultural systems to better capture the responses of $N_r$ emissions to driving factors and provide more comprehensive datasets for evaluating, calibrating, and refining emission models and estimates; 2) refine EFs within the EF approach by incorporating localized adjustments based on extensive field measurements for different crop types, cropping systems and livestock systems across diverse regions; 3) incorporate process-based agroecosystem models with enhanced representation of the nitrogen cycle to improve emission estimates on fine spatiotemporal scales and to capture the episodic and dynamics responses of $N_r$ emissions to fertilizer applications, extreme weather events, and changes in farming practices; 4) utilize geostationary satellite observations with more sophisticated retrieval methods, especially for agricultural burning detection and short-term soil responses to fertilizer applications. These improvements would greatly help devise better control policies. Currently, only the European Union has established $NH_3$ emission control targets, aiming to reduce $NH_3$ emissions by 19% in 2030 compared to 2005 levels, as per the National Emission Ceiling Directive (EU, 2016). In China, in late 2023, a decade after the initial launch of the Action Plan for Fighting for a Blue Sky, new actions were announced to focus on controlling agricultural $NH_3$ emissions (Council, 2023). These included specific targets for the Beijing-Tianjin-Hebei region, aiming for a 5% reduction by 2025 compared to 2020 levels. Other countries and regions are expected to follow suit, and more research for especially poorly researched, developing regions such as those in South Asia, Southeast Asia, Africa and Latin America are necessary to guide their mitigation efforts.

To mitigate food-system emissions of $N_r$ and other pollutants, we also need to focus more research efforts on the various mitigation pathways, including: 1) identifying strategies that can effectively mitigate multiple $N_r$ species and benefit agricultural productivity without exacerbating other $N_r$ losses, acknowledging the trade-offs commonly observed in mitigation strategies; 2) developing customized strategies tailored to the specific conditions of each region, farm or facility, given the variability in the effectiveness of $N_r$ emission control strategies; 3) enhancing our understanding of the costs and outcomes of various mitigation measures, which is crucial for developing socioeconomically sound strategies with minimized additional investment, particularly for low-income regions; 4) emphasizing integrated policies that consider the entire food supply chain and food demand to maximize the socioeconomic and environmental benefits of emission reduction measures.

Greater research efforts in the above can arguably help us address SDG13 “Climate Action” as well, which aims to take urgent action to combat climate change and its impacts, as many of the short-lived $N_r$ species share common sources with $N_2O$, the third most potent greenhouse gas. Furthermore, they also help us strive toward SDG15 “Life on Land”, which aims to protect, restore, and sustainably manage terrestrial ecosystems, promote biodiversity conservation, and combat desertification and land degradation. Nitrogen pollution brings tremendous disruptions to terrestrial ecosystems, often with ramifications for both ecosystem productivity and biodiversity. Although the fates of various agricultural $N_r$ compounds in terrestrial ecosystems may be more within the realm of biogeochemistry, atmospheric scientists are necessary to better quantify the ecosystem input of $N_r$ via atmospheric deposition, especially via (Zhang et al., 2021b): 1) enhancing the $N_r$ deposition monitoring network with a focus on technological innovations for dry deposition measurements and increased spatial resolutions by including more representative sites; 2) improving model-based analysis by better parameterizing both wet and dry deposition processes, as well as by providing more accurate $N_r$ emission estimates to drive model simulations; 3) advancing satellite-based analysis with more refined retrieval methods; 4) developing a comprehensive framework that integrates monitoring, air quality modeling, and satellite observations.

It is essential to consider the mitigation strategies discussed above in synergy with other socioeconomic objectives. For instance, if top-down approaches are used to reform the food systems in ways that ignore the actual needs of the farmers, or even deprive the farmers of their livelihood, cultural heritage and social inclusion, such approaches do not abide to the tenets of sustainability even if they are effective in abating food-system emissions. Indigenous knowledge, cultures and traditions in the local food systems always have to be proactively considered. Often reducing food-system emissions would bring immediate health benefits to the farmers and people in agricultural regions in general due to the reduced exposure to airborne and waterborne (e.g., fertilizer, pesticide and animal waste runoffs) agricultural pollutants, which would in the long term improve their productivity and livelihood. Furthermore, by promoting sustainable agricultural practices, supporting local food production, improving distribution networks and reducing food waste, food system transformation can help both rural and urban populations gain access to safe, nutritious and affordable food, which is essential for fostering socially inclusive communities. Therefore, transforming the food systems in economically feasible, socially equitable and environmentally responsible manners, facilitated by better understanding of the science of agriculture-environment interactions behind, can also help us address SDG1 "No Poverty", which aims to end poverty by addressing its root causes, promoting social protection systems, and enhancing access to basic services and resources; SDG6 "Clean Water and Sanitation", which aims to ensure universal access to clean water and sanitation, improve water quality and promote sustainable water management practices; and SDG11 "Sustainable Cities and Communities", which aims to make cities and human settlements inclusive, safe, resilient and sustainable.

We therefore opine that, in consideration of the substantial impacts of agricultural and food-system emissions on atmospheric chemistry, air pollution and subsequently on terrestrial ecosystems, we as a society need to take concrete actions to transform the food systems, so as to simultaneously ensure food security for the masses, lessen the human health and ecological impacts of agricultural pollutants, improve the livelihood of farmers and agricultural workers, and help cities and communities become economically, socially and environmentally sustainable. That is, in essence, to achieve multiple SDGs. To that end, scientists play vital roles in providing the detailed process-based understanding of agricultural and food-system emissions as well as the fates and wider impacts of the emitted compounds. Above we have specifically highlighted several knowledge gaps and aspects that warrant much more research efforts, which are necessary to guide food-system transformation along technologically and economically feasible as well as socially and environmentally responsible paths. This could be one of the key ways through which we scientists can fulfil not only our professional responsibility, but also our social responsibility.

## Contributions

APKT conceived, wrote and revised the opinion paper, and diagnosed connections of atmospheric chemistry to sustainable development. LL and BL reviewed current literature and drafted most parts on emissions, chemistry and mitigation methods.

## Competing interests

At least one of the (co-)authors is a member of the editorial board of Atmospheric Chemistry and Physics.

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## References

Akiyama, H., Yan, X., and Yagi, K.: Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N2O and NO emissions from agricultural soils: meta-analysis: MITIGATION OPTIONS FOR N2O AND NO EMISSIONS, Global Change Biology, 16, 1837-1846, doi:10.1111/j.1365-2486.2009.02031.x, 2009.

Alexandratos, N. and Bruinsma, J.: World agriculture towards 2030/2050: the 2012 revision, 2012. 2012.

Ansari, A. S. and Pandis, S. N.: Response of Inorganic PM to Precursor Concentrations, Environmental Science & Technology, 32, 2706-2714, doi:10.1021/es971130j, 1998.

Bai, Z., Fan, X., Jin, X., Zhao, Z., Wu, Y., Oenema, O., Velthof, G., Hu, C., and Ma, L.: Relocate 10 billion livestock to reduce harmful nitrogen pollution exposure for 90% of China's population, Nat Food, 3, 152-160, doi:10.1038/s43016-021-00453-z, 2022.

Balasubramanian, S., Domingo, N. G. G., Hunt, N. D., Gittlin, M., Colgan, K. K., Marshall, J. D., Robinson, A. L., Azevedo, I. M. L., Thakrar, S. K., Clark, M. A., Tessum, C. W., Adams, P. J., Pandis, S. N., and Hill, J. D.: The food we eat, the air we breathe: a review of the fine particulate matter-induced air quality health impacts of the global food system, Environmental Research Letters, 16, doi:10.1088/1748-9326/ac065f, 2021.

Balasubramanian, S., McFarland, D. M., Koloutsou-Vakakis, S., Fu, K., Menon, R., Lehmann, C., and Rood, M. J.: Effect of grid resolution and spatial representation of NH<sub>3</sub> emissions from fertilizer application on predictions of NH<sub>3</sub> and PM<sub>2.5</sub> concentrations in the United States Corn Belt, Environmental Research Communications, 2, doi:10.1088/2515-7620/ab6c01, 2020.

Bauer, S. E., Tsigaridis, K., and Miller, R.: Significant atmospheric aerosol pollution caused by world food cultivation, Geophysical Research Letters, 43, 5394-5400, doi:10.1002/2016GL068354, 2016.

Beusen, A. H. W., Bouwman, A. F., Heuberger, P. S. C., Van Drecht, G., and Van Der Hoek, K. W.: Bottom-up uncertainty estimates of global ammonia emissions from global agricultural production systems, Atmospheric Environment, 42, 6067-6077, doi:10.1016/j.atmosenv.2008.03.044, 2008.

Bobbink, R., Hicks, K., Galloway, J., Spranger, T., Alkemade, R., Ashmore, M., Bustamante, M., Cinderby, S., Davidson, E., Dentener, F., Emmett, B., Erisman, J. W., Fenn, M., Gilliam, F., Nordin, A., Pardo, L., and De Vries, W.: Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis, Ecol Appl, 20, 30-59, doi:Doi 10.1890/08-1140.1, 2010.

Bouwman, A. F., Lee, D. S., Asman, W. A. H., Dentener, F. J., Van Der Hoek, K. W., and Olivier, J. G. J.: A global high-resolution emission inventory for ammonia, Global Biogeochemical Cycles, 11, 561-587, doi:10.1029/97gb02266, 1997.

Brundtland, G. H.: Our Common Future - Call for Action, Environ Conserv, 14, 291-294, doi:Doi 10.1017/S0376892900016805, 1987.

Bruulsema, T., Lemunyon, J., and Herz, B.: Know your fertilizer rights, Crops and Soils, 42, 13-18, 2009.

Chen, Y., Hall, J., van Wees, D., Andela, N., Hantson, S., Giglio, L., van der Werf, G. R., Morton, D. C., and Randerson, J. T.: Multi-decadal trends and variability in burned area from the fifth version of the Global Fire Emissions Database (GFED5), Earth System Science Data, 15, 5227-5259, doi:10.5194/essd-15-5227-2023, 2023.

Chen, Y., Shen, H., Shih, J.-S., Russell, A. G., Shao, S., Hu, Y., Odman, M. T., Nenes, A., Pavur, G. K., Zou, Y., Chen, Z., Smith, R. A., Burtraw, D., and Driscoll, C. T.: Greater Contribution From Agricultural Sources to Future Reactive Nitrogen Deposition in the United States, Earth's Future, 8, e2019EF001453, doi:https://doi.org/10.1029/2019EF001453, 2020.

Crippa, M., Guizzardi, D., Butler, T., Keating, T., Wu, R., Kaminski, J., Kuenen, J., Kurokawa, J., Chatani, S., Morikawa, T., Pouliot, G., Racine, J., Moran, M. D., Klimont, Z., Manseau, P. M., Mashayekhi, R., Henderson, B. H., Smith, S. J., Suchyta, H., Muntean, M., Solazzo, E., Banja, M., Schaaf, E., Pagani, F., Woo, J.-H., Kim, J., Monforti-Ferrario, F., Pisoni, E., Zhang, J., Niemi, D., Sassi, M., Ansari, T., and Foley, K.: The HTAP_v3 emission mosaic: merging regional and global monthly emissions (2000–2018) to support air quality modelling and policies, Earth System Science Data, 15, 2667-2694, doi:10.5194/essd-15-2667-2023, 2023.

Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Dentener, F., van Aardenne, J. A., Monni, S., Doering, U., Olivier, J. G. J., Pagliari, V., and Janssens-Maenhout, G.: Gridded emissions of air pollutants for the period 1970–2012 within EDGAR v4.3.2, Earth System Science Data, 10, 1987-2013, doi:10.5194/essd-10-1987-2018, 2018.

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F. N., and Leip, A.: Food systems are responsible for a third of global anthropogenic GHG emissions, Nat. Food, 2, 198-209, doi:10.1038/s43016-021-00225-9, 2021.

Crippa, M., Solazzo, E., Guizzardi, D., Van Dingenen, R., and Leip, A.: Air pollutant emissions from global food systems are responsible for environmental impacts, crop losses and mortality, Nat Food, 3, 942-956, doi:10.1038/s43016-022-00615-7, 2022a.

Crippa, M., Solazzo, E., Guizzardi, D., Van Dingenen, R., and Leip, A.: Air pollutant emissions from global food systems are responsible for environmental impacts, crop losses and mortality, Nature Food, 3, 942-956, doi:10.1038/s43016-022-00615-7, 2022b.

Cusworth, D. H., Mickley, L. J., Sulprizio, M. P., Liu, T., Marlier, M. E., DeFries, R. S., Guttikunda, S. K., and Gupta, P.: Quantifying the influence of agricultural fires in northwest India on urban air pollution in Delhi, India, Environmental Research Letters, 13, doi:10.1088/1748-9326/aab303, 2018.

Davidson, E. A., Suddick, E. C., Rice, C. W., and Prokopy, L. S.: More Food, Low Pollution (Mo Fo Lo Po): A Grand Challenge for the 21st Century, Journal of Environmental Quality, 44, 305-311, doi:https://doi.org/10.2134/jeq2015.02.0078, 2015.

Del Grosso, S. J., Ogle, S. M., Nevison, C., Gurung, R., Parton, W. J., Wagner-Riddle, C., Smith, W., Winiwarter, W., Grant, B., Tenuta, M., Marx, E., Spencer, S., and Williams, S.: A gap in nitrous oxide emission reporting complicates long-term climate mitigation, Proceedings of the National Academy of Sciences, 119, e2200354119, doi:10.1073/pnas.2200354119, 2022.

Del Grosso, S. J., Ojima, D. S., Parton, W. J., Stehfest, E., Heistemann, M., DeAngelo, B., and Rose, S.: Global scale DAYCENT model analysis of greenhouse gas emissions and mitigation strategies for cropped soils, Global and Planetary Change, 67, 44-50, doi:10.1016/j.gloplacha.2008.12.006, 2009.

Domingo, N. G. G., Balasubramanian, S., Thakrar, S. K., Clark, M. A., Adams, P. J., Marshall, J. D., Muller, N. Z., Pandis, S. N., Polasky, S., Robinson, A. L., Tessum, C. W., Tilman, D., Tschofen, P., and Hill, J. D.: Air quality–related health damages of food, Proceedings of the National Academy of Sciences, 118, e2013637118, doi:10.1073/pnas.2013637118, 2021.

FAO: http://faostat3.fao.org/faostat-gateway/go/to/home/E, last access: Jan 2024.

FAO: The future of food and agriculture – Alternative pathways to 2050, Food and Agriculture Organization of the United Nations, Rome, Italy, 224 pp., 2018.

FAO: Pathways towards lower emissions A global assessment of the greenhouse gas emissions and mitigation options from livestock agrifood systems, Rome, 2023.

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O'Connell, C., Ray, D. K., West, P. C., Balzer, C., Bennett, E. M., Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockstrom, J., Sheehan, J., Siebert, S., Tilman, D., and Zaks, D. P. M.: Solutions for a cultivated planet, Nature, 478, 337-342, doi:Doi 10.1038/Nature10452, 2011.

Fowler, D., Coyle, M., Skiba, U., Sutton, M. A., Cape, J. N., Reis, S., Sheppard, L. J., Jenkins, A., Grizzetti, B., Galloway, J. N., Vitousek, P., Leach, A., Bouwman, A. F., Butterbach-Bahl, K., Dentener, F., Stevenson, D., Amann, M., and Voss, M.: The global nitrogen cycle in the twenty-first century, Philos Trans R Soc Lond B Biol Sci, 368, 20130164, doi:10.1098/rstb.2013.0164, 2013.

Fu, X., Wang, S. X., Xing, J., Zhang, X. Y., Wang, T., and Hao, J. M.: Increasing Ammonia Concentrations Reduce the Effectiveness of Particle Pollution Control Achieved via SO<sub>2</sub> and NO<i><sub>X</sub></i> Emissions Reduction in East China, Environmental Science & Technology Letters, 4, 221-227, doi:10.1021/acs.estlett.7b00143, 2017.

Galloway, J. N., Leach, A. M., Bleeker, A., and Erisman, J. W.: A chronology of human understanding of the nitrogen cycle <sup/>, Phil. Trans. R. Soc. B, 368, 20130120, doi:10.1098/rstb.2013.0120, 2013.

GBD: Health effects of dietary risks in 195 countries, 1990-2017: a systematic analysis for the Global Burden of Disease Study 2017, Lancet, 393, 1958-1972, doi:10.1016/S0140-6736(19)30041-8, 2019.

Geddes, J. A., Pusede, S. E., and Wong, A. Y. H.: Changes in the Relative Importance of Biogenic Isoprene and Soil NOx Emissions on Ozone Concentrations in Nonattainment Areas of the United States, Journal of Geophysical Research: Atmospheres, 127, doi:10.1029/2021JD036361, 2022.

Gordon, J. N. D., Bilsback, K. R., Fiddler, M. N., Pokhrel, R. P., Fischer, E. V., Pierce, J. R., and Bililign, S.: The Effects of Trash, Residential Biofuel, and Open Biomass Burning Emissions on Local and Transported PM(2.5) and Its Attributed Mortality in Africa, Geohealth, 7, e2022GH000673, doi:10.1029/2022GH000673, 2023.

Gu, B., Zhang, L., Van Dingenen, R., Vieno, M., Van Grinsven, H. J. M., Zhang, X., Zhang, S., Chen, Y., Wang, S., Ren, C., Rao, S., Holland, M., Winiwarter, W., Chen, D., Xu, J., and Sutton, M. A.: Abating ammonia is more cost-effective than nitrogen oxides for mitigating PM <sub>2.5</sub> air pollution, Science, 374, 758-762, doi:10.1126/science.abf8623, 2021.

Gu, B., Zhang, X., Lam, S. K., Yu, Y., Van Grinsven, H. J. M., Zhang, S., Wang, X., Bodirsky, B. L., Wang, S., Duan, J., Ren, C., Bouwman, L., De Vries, W., Xu, J., Sutton, M. A., and Chen, D.: Cost-effective mitigation of nitrogen pollution from global croplands, Nature, 613, 77-84, doi:10.1038/s41586-022-05481-8, 2023.

Guo, H. Y., Otjes, R., Schlag, P., Kiendler-Scharr, A., Nenes, A., and Weber, R. J.: Effectiveness of ammonia reduction on control of fine particle nitrate, Atmospheric Chemistry and Physics, 18, 12241-12256, doi:10.5194/acp-18-12241-2018, 2018.

Guo, J. H., Liu, X. J., Zhang, Y., Shen, J. L., Han, W. X., Zhang, W. F., Christie, P., Goulding, K. W. T., Vitousek, P. M., and Zhang, F. S.: Significant Acidification in Major Chinese Croplands, Science, 327, 1008-1010, doi:10.1126/science.1182570, 2010.

Guo, Y., Tan, H., Zhang, L., Liu, G., Zhou, M., Vira, J., Hess, P. G., Liu, X., Paulot, F., and Liu, X.: Global food loss and waste embodies unrecognized harms to air quality and biodiversity hotspots, Nat Food, 4, 686-698, doi:10.1038/s43016-023-00810-0, 2023.

Hall, J. V., Zibtsev, S. V., Giglio, L., Skakun, S., Myroniuk, V., Zhuravel, O., Goldammer, J. G., and Kussul, N.: Environmental and political implications of underestimated cropland burning in Ukraine, Environ Res Lett, 16, 064019, doi:10.1088/1748-9326/abfc04, 2021.

Han, X., Zhu, L. Y., Liu, M. X., Song, Y., and Zhang, M. G.: Numerical analysis of agricultural emissions impacts on PM<sub>2.5</sub> in China using a high-resolution ammonia emission inventory, Atmospheric Chemistry and Physics, 20, 9979-9996, doi:10.5194/acp-20-9979-2020, 2020.

Herrero, M., Havlik, P., Valin, H., Notenbaert, A., Rufino, M. C., Thornton, P. K., Blummel, M., Weiss, F., Grace, D., and Obersteiner, M.: Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems, Proc Natl Acad Sci U S A, 110, 20888-20893, doi:10.1073/pnas.1308149110, 2013.

Hill, J., Goodkind, A., Tessum, C., Thakrar, S., Tilman, D., Polasky, S., Smith, T., Hunt, N., Mullins, K., Clark, M., and Marshall, J.: Air-quality-related health damages of maize, Nature Sustainability, 2, 397-403, doi:10.1038/s41893-019-0261-y, 2019.

Holcomb, J. C., Sullivan, D. M., Horneck, D. A., and Clough, G. H.: Effect of Irrigation Rate on Ammonia Volatilization, Soil Science Society of America Journal, 75, 2341-2347, doi:10.2136/sssaj2010.0446, 2011.

Holt, J., Selin, N. E., and Solomon, S.: Changes in Inorganic Fine Particulate Matter Sensitivities to Precursors Due to Large-Scale US Emissions Reductions, Environmental Science & Technology, 49, 4834-4841, doi:10.1021/acs.est.5b00008, 2015.

Hou, Y., Velthof, G. L., and Oenema, O.: Mitigation of ammonia, nitrous oxide and methane emissions from manure management chains: a meta-analysis and integrated assessment, Glob Chang Biol, 21, 1293-1312, doi:10.1111/gcb.12767, 2015.

Houlton, B. Z., Almaraz, M., Aneja, V., Austin, A. T., Bai, E., Cassman, K. G., Compton, J. E., Davidson, E. A., Erisman, J. W., Galloway, J. N., Gu, B., Yao, G., Martinelli, L. A., Scow, K., Schlesinger, W. H., Tomich, T. P., Wang, C., and Zhang, X.: A World of Cobenefits: Solving the Global Nitrogen Challenge, Earth's Future, 7, 865-872, doi:https://doi.org/10.1029/2019EF001222, 2019.

Huang, L., Fang, J., Liao, J., Yarwood, G., Chen, H., Wang, Y., and Li, L.: Insights into soil NO emissions and the contribution to surface ozone formation in China, Atmospheric Chemistry and Physics, 23, 14919-14932, doi:10.5194/acp-23-14919-2023, 2023.

Huang, T. B., Zhu, X., Zhong, Q. R., Yun, X., Meng, W. J., Li, B. G., Ma, J. M., Zeng, E. Y., and Tao, S.: Spatial and Temporal Trends in Global Emissions of Nitrogen Oxides from 1960 to 2014, Environmental Science & Technology, 51, 7992-8000, doi:10.1021/acs.est.7b02235, 2017.

Huang, X., Song, Y., Li, M., Li, J., Huo, Q., Cai, X., Zhu, T., Hu, M., and Zhang, H.: A high-resolution ammonia emission inventory in China, Global Biogeochemical Cycles, 26, doi:10.1029/2011gb004161, 2012.

Hudman, R. C., Moore, N. E., Mebust, A. K., Martin, R. V., Russell, A. R., Valin, L. C., and Cohen, R. C.: Steps towards a mechanistic model of global soil nitric oxide emissions: implementation and space based-constraints, Atmos. Chem. Phys., 12, 7779-7795, doi:10.5194/acp-12-7779-2012, 2012.

Institute, H. E.: State of Global Air 2020, Boston, MA: Health Effects Institute, 2020.

Jickells, T. and Moore, C. M.: The Importance of Atmospheric Deposition for Ocean Productivity, Annual Review of Ecology, Evolution, and Systematics, 46, 481-501, doi:10.1146/annurev-ecolsys-112414-054118, 2015.

Jin, S., Zhang, B., Wu, B., Han, D., Hu, Y., Ren, C., Zhang, C., Wei, X., Wu, Y., Mol, A. P. J., Reis, S., Gu, B., and Chen, J.: Decoupling livestock and crop production at the household level in China, Nature Sustainability, 4, 48-55, doi:10.1038/s41893-020-00596-0, 2020.

Kim, J., Jeong, U., Ahn, M. H., Kim, J. H., Park, R. J., Lee, H., Song, C. H., Choi, Y. S., Lee, K. H., Yoo, J. M., Jeong, M. J., Park, S. K., Lee, K. M., Song, C. K., Kim, S. W., Kim, Y. J., Kim, S. W., Kim, M., Go, S., Liu, X., Chance, K., Chan Miller, C., Al-Saadi, J., Veihelmann, B., Bhartia, P. K., Torres, O., Abad, G. G., Haffner, D. P., Ko, D. H., Lee, S. H., Woo, J. H., Chong, H., Park, S. S., Nicks, D., Choi, W. J., Moon, K. J., Cho, A., Yoon, J., Kim, S. K., Hong, H., Lee, K., Lee, H., Lee, S., Choi, M., Veefkind, P., Levelt, P. F., Edwards, D. P., Kang, M., Eo, M., Bak, J., Baek, K., Kwon, H. A., Yang, J., Park, J., Han, K. M., Kim, B. R., Shin, H. W., Choi, H., Lee, E., Chong, J., Cha, Y., Koo, J. H., Irie, H., Hayashida, S., Kasai, Y., Kanaya, Y., Liu, C., Lin, J., Crawford, J. H., Carmichael, G. R., Newchurch, M. J., Lefer, B. L., Herman, J. R., Swap, R. J., Lau, A. K. H., Kurosu, T. P., Jaross, G., Ahlers, B., Dobber, M., McElroy, C. T., and Choi, Y.: New Era of Air Quality Monitoring from Space: Geostationary Environment Monitoring Spectrometer (GEMS), B. Am. Meteorol. Soc., 101, E1-E22, doi:10.1175/Bams-D-18-0013.1, 2020.

Korontzi, S., McCarty, J., Loboda, T., Kumar, S., and Justice, C.: Global distribution of agricultural fires in croplands from 3 years of Moderate Resolution Imaging Spectroradiometer (MODIS) data, Global Biogeochem. Cycles, 20, doi:10.1029/2005gb002529, 2006.

Lan, R., Eastham, S. D., Liu, T., Norford, L. K., and Barrett, S. R. H.: Air quality impacts of crop residue burning in India and mitigation alternatives, Nat Commun, 13, 6537, doi:10.1038/s41467-022-34093-z, 2022.

Lelieveld, J., Evans, J. S., Fnais, M., Giannadaki, D., and Pozzer, A.: The contribution of outdoor air pollution sources to premature mortality on a global scale, Nature, 525, 367-371, doi:10.1038/nature15371, 2015.

Li, C., Aber, J., Stange, F., Butterbach-Bahl, K., and Papen, H.: A process-oriented model of N <sub>2</sub> O and NO emissions from forest soils: 1. Model development, Journal of Geophysical Research: Atmospheres, 105, 4369-4384, doi:10.1029/1999JD900949, 2000.

Li, Y., Schichtel, B. A., Walker, J. T., Schwede, D. B., Chen, X., Lehmann, C. M. B., Puchalski, M. A., Gay, D. A., and Collett, J. L.: Increasing importance of deposition of reduced nitrogen in the United States, Proceedings of the National Academy of Sciences, 113, 5874-5879, doi:doi:10.1073/pnas.1525736113, 2016.

Lin, M. and Begho, T.: Crop residue burning in South Asia: A review of the scale, effect, and solutions with a focus on reducing reactive nitrogen losses, J Environ Manage, 314, 115104, doi:10.1016/j.jenvman.2022.115104, 2022.

Liu, L., Xu, W., Lu, X., Zhong, B., Guo, Y., Lu, X., Zhao, Y., He, W., Wang, S., Zhang, X., Liu, X., and Vitousek, P.: Exploring global changes in agricultural ammonia emissions and their contribution to nitrogen deposition since 1980, Proceedings of the National Academy of Sciences, 119, e2121998119, doi:doi:10.1073/pnas.2121998119, 2022.

Liu, L., Zhang, X., Xu, W., Liu, X., Zhang, Y., Li, Y., Wei, J., Lu, X., Wang, S., Zhang, W., Zhao, L., Wang, Z., and Wu, X.: Fall of oxidized while rise of reduced reactive nitrogen deposition in China, Journal of Cleaner Production, 272, 122875, doi:https://doi.org/10.1016/j.jclepro.2020.122875, 2020.

Liu, X., Tai, A. P. K., Chen, Y., Zhang, L., Shaddick, G., Yan, X., and Lam, H. M.: Dietary shifts can reduce premature deaths related to particulate matter pollution in China, Nat Food, 2, 997-1004, doi:10.1038/s43016-021-00430-6, 2021a.

Liu, X. Y., Tai, A. P. K., and Fung, K. M.: Responses of surface ozone to future agricultural ammonia emissions and subsequent nitrogen deposition through terrestrial ecosystem changes, Atmos. Chem. Phys., 21, 17743-17758, doi:10.5194/acp-21-17743-2021, 2021b.

Liu, Z. H., Rieder, H. E., Schmidt, C., Mayer, M., Guo, Y. X., Winiwarter, W., and Zhang, L.: Optimal reactive nitrogen control pathways identified for cost-effective PM<sub>2.5</sub> mitigation in Europe, Nature Communications, 14, doi:10.1038/s41467-023-39900-9, 2023.

Liu, Z. H., Zhou, M., Chen, Y. F., Chen, D., Pan, Y. P., Song, T., Ji, D. S., Chen, Q., and Zhang, L.: The nonlinear response of fine particulate matter pollution to ammonia emission reductions in North China, Environmental Research Letters, 16, doi:10.1088/1748-9326/abdf86, 2021c.

Lu, M., Yang, Y. H., Luo, Y. Q., Fang, C. M., Zhou, X. H., Chen, J. K., Yang, X., and Li, B.: Responses of ecosystem nitrogen cycle to nitrogen addition: a meta-analysis, New Phytol, 189, 1040-1050, doi:10.1111/j.1469-8137.2010.03563.x, 2011.

Lu, X., Vitousek, P. M., Mao, Q., Gilliam, F. S., Luo, Y., Turner, B. L., Zhou, G., and Mo, J.: Nitrogen deposition accelerates soil carbon sequestration in tropical forests, Proceedings of the National Academy of Sciences, 118, e2020790118, doi:doi:10.1073/pnas.2020790118, 2021a.

Lu, X., Ye, X., Zhou, M., Zhao, Y., Weng, H., Kong, H., Li, K., Gao, M., Zheng, B., Lin, J., Zhou, F., Zhang, Q., Wu, D., Zhang, L., and Zhang, Y.: The underappreciated role of agricultural soil nitrogen oxide emissions in ozone pollution regulation in North China, Nature Communications, 12, 5021, doi:10.1038/s41467-021-25147-9, 2021b.

Luo, L., Cohan, D. S., Masiello, C. A., Lychuk, T. E., and Gao, X.: Agroecosystem modeling of reactive nitrogen emissions from U.S. agricultural soils with carbon amendments, Biochar, 5, 72, doi:10.1007/s42773-023-00271-5, 2023.

Luo, L., Ran, L., Rasool, Q. Z., and Cohan, D. S.: Integrated Modeling of U.S. Agricultural Soil Emissions of Reactive Nitrogen and Associated Impacts on Air Pollution, Health, and Climate, Environmental Science & Technology, doi: 10.1021/acs.est.1c08660, 2022a. acs.est.1c08660, doi:10.1021/acs.est.1c08660, 2022a.

Luo, Z. Q., Zhang, Y. Z., Chen, W., Van Damme, M., Coheur, P. F., and Clarisse, L.: Estimating global ammonia (NH
) emissions based on IASI observations from 2008 to 2018, Atmospheric Chemistry and Physics, 22, 10375-10388, doi:10.5194/acp-22-10375-2022, 2022b.

Ma, R., Zou, J., Han, Z., Yu, K., Wu, S., Li, Z., Liu, S., Niu, S., Horwath, W. R., and Zhu-Barker, X.: Global soil-derived ammonia emissions from agricultural nitrogen fertilizer application: A refinement based on regional and crop-specific emission factors, Glob Chang Biol, 27, 855-867, doi:10.1111/gcb.15437, 2021.

McDuffie, E. E., Smith, S. J., O'Rourke, P., Tibrewal, K., Venkataraman, C., Marais, E. A., Zheng, B., Crippa, M., Brauer, M., and Martin, R. V.: A global anthropogenic emission inventory of atmospheric pollutants from sector- and fuel-specific sources (1970–2017): an application of the Community Emissions Data System (CEDS), Earth System Science Data, 12, 3413-3442, doi:10.5194/essd-12-3413-2020, 2020.

Misselbrook, T. H., Van Der Weerden, T. J., Pain, B. F., Jarvis, S. C., Chambers, B. J., Smith, K. A., Phillips, V. R., and Demmers, T. G. M.: Ammonia emission factors for UK agriculture, Atmospheric Environment, 34, 871-880, doi:10.1016/s1352-2310(99)00350-7, 2000.

Miyazaki, K., Eskes, H., Sudo, K., Boersma, K. F., Bowman, K., and Kanaya, Y.: Decadal changes in global surface NO
emissions from multi-constituent satellite data assimilation, Atmospheric Chemistry and Physics, 17, 807-837, doi:10.5194/acp-17-807-2017, 2017.

Nelson, A. J., Lichiheb, N., Koloutsou-Vakakis, S., Rood, M. J., Heuer, M., Myles, L., Joo, E., Miller, J., and Bernacchi, C.: Ammonia flux measurements above a corn canopy using relaxed eddy accumulation and a flux gradient system, Agricultural and Forest Meteorology, 264, 104-113, doi:https://doi.org/10.1016/j.agrformet.2018.10.003, 2019.

Nematian, M., Ng'ombe, J. N., and Keske, C.: Sustaining agricultural economies: regional economic impacts of biochar production from waste orchard biomass in California's Central Valley, Environment, Development and Sustainability, doi: 10.1007/s10668-023-03984-6, 2023. doi:10.1007/s10668-023-03984-6, 2023.

Oswald, R., Behrendt, T., Ermel, M., Wu, D., Su, H., Cheng, Y., Breuninger, C., Moravek, A., Mougin, E., Delon, C., Loubet, B., Pommerening-Röser, A., Sörgel, M., Pöschl, U., Hoffmann, T., Andreae, M. O., Meixner, F. X., and Trebs, I.: HONO Emissions from Soil Bacteria as a Major Source of Atmospheric Reactive Nitrogen, Science, 341, 1233-1235, doi:10.1126/science.1242266, 2013.

Pan, S.-Y., He, K.-H., Lin, K.-T., Fan, C., and Chang, C.-T.: Addressing nitrogenous gases from croplands toward low-emission agriculture, npj Climate and Atmospheric Science, 5, 43, doi:10.1038/s41612-022-00265-3, 2022.

Pinder, R. W., Adams, P. J., and Pandis, S. N.: Ammonia emission controls as a cost-effective strategy for reducing atmospheric particulate matter in the eastern United States, Environmental Science & Technology, 41, 380-386, doi:10.1021/es060379a, 2007.

Pozzer, A., Tsimpidi, A. P., Karydis, V. A., de Meij, A., and Lelieveld, J.: Impact of agricultural emission reductions on fine-particulate matter and public health, Atmospheric Chemistry and Physics, 17, 12813-12826, doi:10.5194/acp-17-12813-2017, 2017.

Qiao, C., Liu, L., Hu, S., Compton, J. E., Greaver, T. L., and Li, Q.: How inhibiting nitrification affects nitrogen cycle and reduces environmental impacts of anthropogenic nitrogen input, Global Change Biology, 21, 1249-1257, doi:10.1111/gcb.12802, 2015.

Quinn Thomas, R., Canham, C. D., Weathers, K. C., and Goodale, C. L.: Increased tree carbon storage in response to nitrogen deposition in the US, Nature Geoscience, 3, 13-17, doi:10.1038/ngeo721, 2010.

Reddington, C. L., Conibear, L., Robinson, S., Knote, C., Arnold, S. R., and Spracklen, D. V.: Air Pollution From Forest and Vegetation Fires in Southeast Asia Disproportionately Impacts the Poor, Geohealth, 5, doi:10.1029/2021gh000418, 2021.

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., Petri, S., Porkka, M.,

Rahmstorf, S., Schaphoff, S., Thonicke, K., Tobian, A., Virkki, V., Wang-Erlandsson, L., Weber, L., and Rockström, J.: Earth beyond six of nine planetary boundaries, Sci Adv, 9, doi:ARTN eadh2458
10.1126/sciadv.adh2458, 2023.

Romer, P. S., Duffey, K. C., Wooldridge, P. J., Edgerton, E., Baumann, K., Feiner, P. A., Miller, D. O., Brune, W. H., Koss, A. R., de Gouw, J. A., Misztal, P. K., Goldstein, A. H., and Cohen, R. C.: Effects of temperature-dependent NO&lt;sub&gt;&lt;i&gt;x&lt;/i&gt;&lt;/sub&gt; emissions on continental ozone production, Atmospheric Chemistry and Physics, 18, 2601-2614, doi:10.5194/acp-18-2601-2018, 2018.

Sha, T., Ma, X., Zhang, H., Janechek, N., Wang, Y., Wang, Y., García, L. C., Jenerette, G. D., and Wang, J.: Impacts of Soil NOx Emission on O3 Air Quality in Rural California, Environ. Sci. Technol., doi: https://dx.doi.org/10.1021/acs.est.0c06834, 2021. 10, doi:https://dx.doi.org/10.1021/acs.est.0c06834, 2021.

Shafiee-Jood, M. and Cai, X.: Reducing Food Loss and Waste to Enhance Food Security and Environmental Sustainability, Environ Sci Technol, 50, 8432-8443, doi:10.1021/acs.est.6b01993, 2016.

Simkin, S. M., Allen, E. B., Bowman, W. D., Clark, C. M., Belnap, J., Brooks, M. L., Cade, B. S., Collins, S. L., Geiser, L. H., Gilliam, F. S., Jovan, S. E., Pardo, L. H., Schulz, B. K., Stevens, C. J., Suding, K. N., Throop, H. L., and Waller, D. M.: Conditional vulnerability of plant diversity to atmospheric nitrogen deposition across the United States, Proceedings of the National Academy of Sciences, 113, 4086-4091, doi:doi:10.1073/pnas.1515241113, 2016.

Song, S., Nenes, A., Gao, M., Zhang, Y., Liu, P., Shao, J., Ye, D., Xu, W., Lei, L., Sun, Y., Liu, B., Wang, S., and McElroy, M. B.: Thermodynamic Modeling Suggests Declines in Water Uptake and Acidity of Inorganic Aerosols in Beijing Winter Haze Events during 2014/2015–2018/2019, Environmental Science & Technology Letters, 6, 752-760, doi:10.1021/acs.estlett.9b00621, 2019.

Springmann, M., Van Dingenen, R., Vandyck, T., Latka, C., Witzke, P., and Leip, A.: The global and regional air quality impacts of dietary change, Nat. Commun., 14, doi:ARTN 6227
10.1038/s41467-023-41789-3, 2023.

Tai, A. P. K. and Martin, M. V.: Impacts of ozone air pollution and temperature extremes on crop yields: Spatial variability, adaptation and implications for future food security, Atmos. Environ., 169, 11-21, doi:10.1016/j.atmosenv.2017.09.002, 2017.

Tai, A. P. K., Martin, M. V., and Heald, C. L.: Threat to future global food security from climate change and ozone air pollution, Nat. Clim. Change, 4, 817-821, doi:10.1038/Nclimate2317, 2014.

Tan, J., Fu, J. S., and Seinfeld, J. H.: Ammonia emission abatement does not fully control reduced forms of nitrogen deposition, Proceedings of the National Academy of Sciences, 117, 9771-9775, doi:doi:10.1073/pnas.1920068117, 2020.

Thakrar, S. K., Balasubramanian, S., Adams, P. J., Azevedo, I. M. L., Muller, N. Z., Pandis, S. N., Polasky, S., Pope, C. A., Robinson, A. L., Apte, J. S., Tessum, C. W., Marshall, J. D., and Hill, J. D.: Reducing Mortality from Air Pollution in the United States by Targeting Specific Emission Sources, Environmental Science & Technology Letters, 7, 639-645, doi:10.1021/acs.estlett.0c00424, 2020.

Thomas, R. Q., Canham, C. D., Weathers, K. C., and Goodale, C. L.: Increased tree carbon storage in response to nitrogen deposition in the US, Nat. Geosci., 3, 13-17, doi:10.1038/Ngeo721, 2010.

Thunis, P., Clappier, A., Beekmann, M., Putaud, J. P., Cuvelier, C., Madrazo, J., and de Meij, A.: Non-linear response of PM
to changes in NO
and NH
emissions in the Po basin (Italy): consequences for air quality plans, Atmos. Chem. Phys., 21, 9309-9327, doi:10.5194/acp-21-9309-2021, 2021.

Tschofen, P., Azevedo, I. L., and Muller, N. Z.: Fine particulate matter damages and value added in the US economy, Proceedings of the National Academy of Sciences of the United States of America, 116, 19857-19862, doi:10.1073/pnas.1905030116, 2019.

Uwizeye, A., de Boer, I. J. M., Opio, C. I., Schulte, R. P. O., Falcucci, A., Tempio, G., Teillard, F., Casu, F., Rulli, M., Galloway, J. N., Leip, A., Erisman, J. W., Robinson, T. P., Steinfeld, H., and Gerber, P. J.: Nitrogen emissions along global livestock supply chains, Nature Food, 1, 437-446, doi:10.1038/s43016-020-0113-y, 2020.

van der Werf, G. R., Randerson, J. T., Giglio, L., van Leeuwen, T. T., Chen, Y., Rogers, B. M., Mu, M., van Marle, M. J. E., Morton, D. C., Collatz, G. J., Yokelson, R. J., and Kasibhatla, P. S.: Global fire emissions estimates during 1997–2016, Earth System Science Data, 9, 697-720, doi:10.5194/essd-9-697-2017, 2017.

Vigan, A., Hassouna, M., Guingand, N., Brame, C., Edouard, N., Eglin, T., Espagnol, S., Eugène, M., Génermont, S., Lagadec, S., Lorinquer, E., Loyon, L., Ponchant, P., and Robin, P.: Development of a Database to Collect Emission Values for Livestock Systems, Journal of Environmental Quality, 48, 1899-1906, doi:10.2134/jeq2019.01.0007, 2019.

Vira, J., Hess, P., Melkonian, J., and Wieder, W. R.: An improved mechanistic model for ammonia volatilization in Earth system models: Flow of Agricultural Nitrogen version 2 (FANv2), Geoscientific Model Development, 13, 4459-4490, doi:10.5194/gmd-13-4459-2020, 2020.

Wang, Y., Fu, X., Wang, T., Ma, J., Gao, H., Wang, X., and Pu, W.: Large Contribution of Nitrous Acid to Soil-Emitted Reactive Oxidized Nitrogen and Its Effect on Air Quality, Environmental Science & Technology, 57, 3516-3526, doi:10.1021/acs.est.2c07793, 2023.

Wang, Y., Fu, X., Wu, D., Wang, M., Lu, K., Mu, Y., Liu, Z., Zhang, Y., and Wang, T.: Agricultural Fertilization Aggravates Air Pollution by Stimulating Soil Nitrous Acid Emissions at High Soil Moisture, Environmental Science & Technology, 55, 14556-14566, doi:10.1021/acs.est.1c04134, 2021.

Wrage-Mönnig, N., Horn, M. A., Well, R., Müller, C., Velthof, G., and Oenema, O.: The role of nitrifier denitrification in the production of nitrous oxide revisited, Soil Biology and Biochemistry, 123, A3-A16, doi:10.1016/j.soilbio.2018.03.020, 2018.

Yan, X., Ying, Y., Li, K., Zhang, Q., and Wang, K.: A review of mitigation technologies and management strategies for greenhouse gas and air pollutant emissions in livestock production, J Environ Manage, 352, 120028, doi:10.1016/j.jenvman.2024.120028, 2024.

Yang, Y., Liu, L., Zhou, W., Guan, K., Tang, J., Kim, T., Grant, R. F., Peng, B., Zhu, P., Li, Z., Griffis, T. J., and Jin, Z.: Distinct driving mechanisms of non-growing season N2O emissions call for spatial-specific mitigation strategies in the US Midwest, Agricultural and Forest Meteorology, 324, 109108, doi:10.1016/j.agrformet.2022.109108, 2022.

Yang, Y. Y., Liu, L., Liu, P., Ding, J., Xu, H., and Liu, S.: Improved global agricultural crop- and animal-specific ammonia emissions during 1961-2018, Agriculture Ecosystems & Environment, 344, doi:ARTN 108289
10.1016/j.agee.2022.108289, 2023.

Zhang, C. H., Guo, H. R., Huang, H., Ma, T. Y., Song, W., Chen, C. J., and Liu, X. Y.: Atmospheric nitrogen deposition and its responses to anthropogenic emissions in a global hotspot region, Atmos Res, 248, doi:ARTN 105137
10.1016/j.atmosres.2020.105137, 2021a.

Zhang, Q., Li, Y. A., Wang, M. R., Wang, K., Meng, F. L., Liu, L., Zhao, Y. H., Ma, L., Zhu, Q. C., Xu, W., and Zhang, F. S.: Atmospheric nitrogen deposition: A review of quantification methods and its spatial pattern derived from the global monitoring networks, Ecotox Environ Safe, 216, doi:ARTN 112180
10.1016/j.ecoenv.2021.112180, 2021b.

Zhang, T., de Jong, M. C., Wooster, M. J., Xu, W., and Wang, L.: Trends in eastern China agricultural fire emissions derived from a combination of geostationary (Himawari) and polar (VIIRS) orbiter fire radiative power products, Atmospheric Chemistry and Physics, 20, 10687-10705, doi:10.5194/acp-20-10687-2020, 2020a.

Zhang, T., Wooster, M., de Jong, M., and Xu, W.: How Well Does the 'Small Fire Boost' Methodology Used within the GFED4.1s Fire Emissions Database Represent the Timing, Location and Magnitude of Agricultural Burning?, Remote Sensing, 10, doi:10.3390/rs10060823, 2018.

Zhang, X., Davidson, E. A., Mauzerall, D. L., Searchinger, T. D., Dumas, P., and Shen, Y.: Managing nitrogen for sustainable development, Nature, 528, 51-59, doi:10.1038/nature15743, 2015.

Zhang, X., Gu, B., van Grinsven, H., Lam, S. K., Liang, X., Bai, M., and Chen, D.: Societal benefits of halving agricultural ammonia emissions in China far exceed the abatement costs, Nat Commun, 11, 4357, doi:10.1038/s41467-020-18196-z, 2020b.

Zhao, Y. H., Zhang, L., Tai, A. P. K., Chen, Y. F., and Pan, Y. P.: Responses of surface ozone air quality to anthropogenic nitrogen deposition in the Northern Hemisphere, Atmos. Chem. Phys., 17, 9781-9796, doi:10.5194/acp-17-9781-2017, 2017.

Zoogman, P., Liu, X., Suleiman, R. M., Pennington, W. F., Flittner, D. E., Al-Saadi, J. A., Hilton, B. B., Nicks, D. K., Newchurch, M. J., Carr, J. L., Janz, S. J., Andraschko, M. R., Arola, A., Baker, B. D., Canova, B. P., Chan Miller, C., Cohen, R. C., Davis, J. E., Dussault, M. E., Edwards, D. P., Fishman, J., Ghulam, A., González Abad, G., Grutter, M., Herman, J. R., Houck, J., Jacob, D. J., Joiner, J., Kerridge, B. J., Kim, J., Krotkov, N. A., Lamsal, L., Li, C., Lindfors, A., Martin, R. V., McElroy, C. T., McLinden, C., Natraj, V., Neil, D. O., Nowlan, C. R., O′Sullivan, E. J., Palmer, P. I., Pierce, R. B., Pippin, M. R., Saiz-Lopez, A., Spurr, R. J. D., Szykman, J. J., Torres, O., Veefkind, J. P., Veihelmann, B., Wang, H., Wang, J., and Chance, K.: Tropospheric emissions: Monitoring of pollution (TEMPO), Journal of Quantitative Spectroscopy and Radiative Transfer, 186, 17-39, doi:https://doi.org/10.1016/j.jqsrt.2016.05.008, 2017.