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

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Abstract

The global food system is essential for the health and wellbeing of society, but is also a major cause of environmental damage. Some impacts, such as on climate change, have been the subject of intense recent inquiry, but others, such as on air quality, are not as well understood. Here, we systematically synthesize the literature to identify the impacts on ambient PM$_{2.5}$ (particulate matter with diameter $\leq 2.5 \mu m$), which is the strongest contributor to premature mortality from exposure to air pollution. Our analysis indicates that the life-cycle of the global food system (pre-production, production, post-production, consumption and waste management) accounts for 58% of anthropogenic, global emissions of primary PM$_{2.5}$, 72% of ammonia (NH$_3$), 13% of nitrogen oxides (NO$_x$), 9% of sulfur dioxide (SO$_2$), and 19% of non-methane volatile organic compounds (NMVOC). These emissions result in at least 890 000 ambient PM$_{2.5}$-related deaths, which is equivalent to 23% of ambient PM$_{2.5}$-related deaths reported in the Global Burden of Disease Study 2015. Predominant contributors include livestock and crop production, which contribute $>50\%$ of food-related NH$_3$ emissions, and land-use change and waste burning, which contribute up to 95% of food-related primary PM$_{2.5}$ emissions. These findings are largely underestimated given the paucity of data from the post-production and consumption stages, total underestimates in NH$_3$ emissions, lack of sector-scale analysis of PM$_{2.5}$-related deaths in South America and Africa, and uncertainties in integrated exposure-response functions. In addition, we identify mitigation opportunities—including shifts in food demand, changes in agricultural practices, the adoption of clean and low-energy technologies, and policy actions—that can facilitate meeting food demand with minimal PM$_{2.5}$ impacts. Further research is required to resolve sectoral-scale, region-specific contributions to PM$_{2.5}$-related deaths, and assess the efficiency of mitigation strategies. Our review is positioned to inform stakeholders, including scientists, engineers, policymakers, farmers and the public, of the health impacts of reduced air quality resulting from the global food system.
## Contents

1. Introduction 3
2. Data and methods 3
3. PM$_{2.5}$ pollution burden from the global food system 5
   3.1. Sectoral-scale emissions: description and estimates 5
       3.1.1. Pre-production 6
       3.1.2. Agricultural production 8
       3.1.3. Post-production 10
       3.1.4. Food preparation and consumption sectors 10
       3.1.5. End-of-life disposal practices 12
3.2. Global emissions inventories 12
4. PM$_{2.5}$ exposure and PM$_{2.5}$-attributable deaths from the food system 13
   4.1. Connecting the emissions—PM$_{2.5}$ exposure—premature mortality pathways 13
   4.2. Global food system linked to significant PM$_{2.5}$-attributable premature deaths 15
       4.2.1. Summary of studies discussing the impact on ambient PM$_{2.5}$-attributable premature deaths 15
       4.2.2. Estimate of ambient PM$_{2.5}$-attributable premature deaths resulting from the global food system 18
       4.2.3. Household cooking impacts on ambient PM$_{2.5}$ pollution burden 20
   4.3. Sources of uncertainties 20
       4.3.1. Characterization of NH$_3$ emissions and linkages to PM$_{2.5}$ formation 20
       4.3.2. Resolving uncertainties in AQMs and choice of model parametrization 20
       4.3.3. Exploring IER functions to link PM$_{2.5}$ exposure to PM$_{2.5}$-attributable deaths 21
5. Opportunities for PM$_{2.5}$ mitigation and policy implications 21
   5.1. ‘Eating enough’ and ‘eating right’ 21
   5.2. Managing food waste 22
   5.3. Farm-scale interventions 22
   5.4. Technological interventions 23
   5.5. Regulatory instruments 23
   5.6. Legislation, environmental and health protections 23
6. Highlights and research needs 24
Data availability statement 25
Acknowledgments 25
References 25
1. Introduction

Global food demand increased threefold from 1960 to 2010 as a result of increasing population, rising incomes, and shifting dietary choices (Foley et al 2011, Tilman et al 2011). This demand has been met by intensive agricultural practices associated with ‘Green Revolution’ technologies, changing land management practices, and resource inputs as evidenced by a 700% increase in nitrogen fertilizer use, a 70% increase in irrigated cropland, and a 110% increase in land cultivation that now accounts for nearly 38% of Earth’s terrestrial surface (Foley et al 2005, Ramankutty et al 2018). Consequently, agricultural intensification has resulted in widespread environmental damage including surface water eutrophication, groundwater contamination, hypoxia and the formation of dead zones in oceans, increased soil acidity associated with reduced crop productivity, biodiversity loss, climate change, and reduced air quality (Vermeulen et al 2012, Erisman et al 2013, Bauer et al 2016, Springmann et al 2018a).

Air pollution is the leading environmental risk factor for mortality, linked to 3.9 million premature deaths in 2017 from exposure to ambient fine particulate matter (PM$_{2.5}$, PM with diameter <2.5 μm) (Landrigan et al 2018, IHME 2020). Atmospheric PM$_{2.5}$ can result either through direct emissions as primary PM$_{2.5}$ or is formed through chemical reactions as secondary PM$_{2.5}$ from precursors that include ammonia (NH$_3$), nitrogen oxide (NO$_x$), sulfur dioxide (SO$_2$) and non-methane volatile organic compounds (NMVOC). Of all air pollutants, PM$_{2.5}$ is the strongest contributor to premature mortality, resulting largely from respiratory disorders, cardiovascular disease and stroke (Burnett et al 2018), and thus is widely regulated with the goal of reducing ambient PM$_{2.5}$ concentrations. PM$_{2.5}$ is short-lived in the atmosphere with a lifetime of a few days to a week, but it can be transported regionally, resulting in human health damage up to several thousand kilometers downwind from the source itself (Wang and Zhang 2014, Goodkind et al 2019).

Historically, emissions reductions of PM$_{2.5}$ and precursor pollutants have been achieved by regulating major anthropogenic sources, such as power plants, industries and transportation (Bachmann et al 2007). Of emerging concern is agriculture, which has been identified as a significant contributor to global ambient PM$_{2.5}$ (Bauer et al 2016, Giannadaki et al 2018) and is linked to nearly 20% of all global ambient PM$_{2.5}$-related deaths (Lelieveld et al 2015). In the United States, emissions from agriculture have been linked to 15%-25% of all PM$_{2.5}$-attributable deaths (Goodkind et al 2019, Thakrar et al 2020). Giannadaki et al (2018) presented an economic case to mitigate agricultural emissions in Europe, finding that a 50% reduction in emissions could reduce PM$_{2.5}$ premature deaths by 18%, with a saving of 89 billion USD.

Most research examining air pollution from the global food system focuses on agriculture (e.g. Aneja et al 2015), but the global food system is expansive and encompasses all life cycle stages of food production, use and disposal (Vermeulen et al 2012). Few studies have examined the human health damage that results from air pollution generated by the global food system (Sun et al 2017). Here, we present a systematic review and an order of magnitude estimate of the contribution of emissions from the global food system to ambient PM$_{2.5}$-attributable deaths. We expand beyond the historical focus on agricultural production to account for emissions from sectors associated with the pre-production, post-production, consumption and waste management of food. Specifically, we follow the causal chain of emissions to health impacts to (a) describe emission pathways and determine national-scale emission totals for 15 sectors within the food system that emit five pollutants of interest (primary PM$_{2.5}$, NH$_3$, NMVOC, NO$_x$, SO$_2$), (b) summarize studies that estimate impacts of sector-scale emissions on ambient PM$_{2.5}$ formation and PM$_{2.5}$-attributable deaths and (c) identify strategies to reduce PM$_{2.5}$ pollution burden within and outside farms. By adopting a system-scale approach that expands beyond the historical focus on agricultural production, our review establishes emissions contributions and PM$_{2.5}$-attributable deaths resulting over the life-cycle of the global food system.

2. Data and methods

To define the overall scope of this review, we first determined the five key stages that span the lifecycle of the global food system by building on the concept of Vermeulen et al (2012). We then identified emissions sectors within each stage of the food system based on the emissions categories defined by the EMEP/EEA (European Monitoring and Evaluation Programme by the European Environment Agency) inventory guidebook, and used the Nomenclature for Reporting to establish system boundaries for each sector (EEA 2016). We also identified and gap-filled the missing sector of land-use change. Our efforts resulted in 15 emissions sectors aggregated by five stages, as shown in figure 1: (a) pre-production: land-use change, fertilizer production, (b) production: on-farm energy use, manure management, grazing, fertilizer use, agricultural waste burning, and other, (on-farm handling of agricultural products, standing crop emissions), (c) post-production: food industry, retail and distribution, transportation, (d) consumption: commercial cooking, residential cooking (not reported in this review), and (e) waste: open burning, controlled disposal (open disposal, uncontrolled incineration, controlled incineration, landfilling and composting).
Figure 1. Schematic of the global food system. Identified are 15 emission sources from the following stages: (a) pre-production: land-use change, fertilizer production, (b) production: on-farm energy use, manure management, grazing, fertilizer use, agricultural waste burning, other (on-farm handling of agricultural products, standing crop emissions), (c) post-production: food industry, retail and distribution, transportation, (d) consumption: commercial cooking, residential cooking (marked in the dotted box as emission budgets; not reported in this review), and (e) waste: open burning, controlled disposal (open disposal, uncontrolled incineration, controlled incineration, landfill and composting).

We then adopted a systematic approach to identify and select relevant scientific literature and analyze relevant findings as defined by Uman (2011). First, the literature was located using scientific databases (Scopus, Google Scholar and Web of Science) by iteratively choosing the preliminary keywords of ‘agriculture’, ‘emissions’, ‘food’, ‘air pollution’, ‘PM$_{2.5}$’ and ‘premature mortality’. This search yielded 4746 peer-reviewed English language publications from the past decade (2009–2020). However, this process did not identify several key studies that examined specific emission sectors. Thus, we systematically expanded the search using additional keywords, by using a combination of each of the 15 emissions sectors, pollutants (PM$_{2.5}$, NH$_3$, NO$_x$, SO$_2$, NMVOC), and mitigation strategies (see table 1) to identify an additional 1384 publications. We then applied the following criteria to sub-select relevant studies based on their abstract and introduction sections. Inclusion criteria were: (a) description of mechanisms and magnitudes of primary PM$_{2.5}$ and secondary PM$_{2.5}$ precursor emissions, (b) air quality studies to quantify the enhancement of secondary ambient PM$_{2.5}$ and (c) mitigation strategies to reduce the PM$_{2.5}$ pollution burden. Exclusion criteria were: (a) hazardous air pollutant emissions from agriculture, (b) ground-level ozone formation and (c) sub-national scale studies using both modeling and measurement approaches to study contributions of the food system to ambient PM$_{2.5}$ concentrations. As a caveat, we do not explicitly show trade and associated emissions flows; instead, emissions are attributed to the geographic domains where sources are located. External to the scope of this review are related topics such as air pollution impacts on agricultural productivity, atmospheric deposition impacts of reactive nitrogen on ecosystems, pathways of global food demand and dietary shifts.

In addition to the archival literature, we also obtained data from highly curated institutional repositories to ensure consistency in data quality across geographic domains. The main data set of interest is the Emissions Database for Global Atmospheric Research (EDGAR4.3.2) that reports annual emissions of primary PM$_{2.5}$ and PM$_{2.5}$ precursors that are differentiated by activity, use of fuel and technology, pollutant type and end of pipe abatement (Crippa et al 2018). We also scoped the following databases: EMEP/EEA emissions factor database (EEA 2016) for sectoral-scale and pollutant-specific emissions factors, the World Bank for demographic (World Bank 2020) and waste management data (World Bank 2018a), FAOSTAT for data on land-use and land-use change, food production, fertilizer production and livestock management (FAO 2020a), the Global Fire Emissions Database (GFED4) for landscape fire data (van der Werf et al 2017), and environmentally extended input-output models including the World Input-Output Database (WIOD)
Table 1. List of search keywords implemented in this study. The search resulted in a database of 6130 records, of which 320 studies, data sets and reports were synthesized in this analysis.

| First iteration          | Subsequent iterations          |
|--------------------------|-------------------------------|
| Agriculture              | Land-use change               |
| Food                     | Deforestation                 |
| Emissions                | Peatland                      |
| Air pollution            | Agriculture driven land-use   |
| PM$_{2.5}$               | Fertilizer production         |
| Premature mortality      | Fertilizer                    |
| Excess deaths            | Peatland                      |
| Livestock                | Fertilizer                    |
| Crop                     | Energy use                    |
| Food industry            | Fuel use                      |
| Cooking                  | Fuel type                     |
| Waste                    | Machine units                 |
| (Timmer et al 2012) and EXIOBASE3.3.17 (Merciai and Schmidt 2016, 2018) for emissions from fertilizer production and the food industry. Overall, of the 6130 records identified, 322 studies, data sets and reports have been synthesized in this review. Of these, only 19 studies established PM$_{2.5}$-attributable health damage either as premature deaths or economic damage from sectors relevant but not exclusive in terms of contributions to the global food system. Only two studies by Sun et al (2017) and Malley et al (2021) examine linkages between air quality and the global food system. Sun et al (2017) qualitatively linked the air quality impacts on the production and processing of food, human health in the form of productivity, and the role of markets, trade, and agricultural and energy policies, while Malley et al (2021) employed an air quality model to estimate the impacts of emissions from global food production on PM$_{2.5}$-related deaths. Here, we explicitly present national-scale emissions contributions of primary PM$_{2.5}$ and secondary PM$_{2.5}$ precursors from the global food system, and synthesize studies that link these emissions to increases in ambient PM$_{2.5}$ exposure and premature deaths. We organize the rest of our review as follows: section 3 provides a description and estimates of sector-specific, national-scale emissions of primary PM$_{2.5}$ and secondary PM$_{2.5}$ precursors; section 4 summarizes the resulting impacts on ambient PM$_{2.5}$ and premature mortality; section 5 identifies tools to reduce PM$_{2.5}$ pollution from the food system, and section 6 presents highlights and conclusions.

3. PM$_{2.5}$ pollution burden from the global food system

3.1. Sectoral-scale emissions: description and estimates

There are multiple approaches to developing air pollutant emissions inventories. A common approach is the use of emission factors, which represent how much pollutant is emitted by a unit of source activity. The emission-factor approach is readily scalable across regions and thus widely implemented, such as in the National Emissions Inventory for the United States (US EPA 2018) and EDGAR4.3.2 (Crippa et al 2018). Other approaches, particularly for agricultural production, include the use of process models that simulate physical, chemical and biological processes governing pollutant release at the field scale (Brilli et al 2017), and are integrated to develop regional-scale emissions inventories as input to air quality models (AQMs) (Cooter et al 2012, Balasubramanian et al 2015). Inverse modeling approaches have also been used recently to constrain emissions using observations assimilated from
ground or satellite platforms, as in the case of improving the seasonality in \(NH_3\) emissions (Zhu et al. 2015b, van Damme et al. 2018). We derive sector-specific, national-scale emissions of \(PM_{2.5}\) and \(PM_{2.5}\) precursors from EDGAR4.3.2 (Crippa et al. 2018) that have been widely used as input to AQMs. EDGAR4.3.2 uses the Nomenclature for Reporting to establish system boundaries for sectors that follow initiatives such as the Convention on Long-Range Transboundary Air Pollution to minimize double-counting of emissions (EEA 2016). However, not all the emissions from the food system are accounted for in EDGAR4.3.2, and for many sectors, these emissions are not explicitly reported for the food system. We have thus supplemented data from other databases including GFED4 (van der Werf et al. 2017) to estimate land-use change emissions and environmentally extended input-output models, such as WIOD (Timmer et al. 2012) and EXIOBASE3.3.17 (Merciai and Schmidt 2016, 2018) for emissions from fertilizer production, food industry and waste, using similar system boundary definitions. We also identified the share of production for food versus non-food purposes based on data reported in the National Food Balance Sheets (FAO 2020b) and applied the fractional contribution of food to estimate emissions for relevant sectors. We present an in-depth discussion of each sector in section 3.1.1 and provide a summary in table 2.

### 3.1.1. Pre-production

#### 3.1.1.1. Land-use change

Agriculture is the primary driver of deforestation especially in the tropical regions of South America and Southeast Asia (Fuchs et al. 2018, Song et al. 2018), and is largely driven by global food demand and international trade (Pendrill et al. 2019). As of 2000, 50% of the habitable land has been diverted to grow food for human consumption and feed for livestock production (Ellis et al. 2010). Increasing demand for food crops, cattle and timber has been linked to recent increases in forest clearing since 2017 in the Brazilian Amazon (De Oliveira et al. 2020) and industrial oil palm productions in equatorial South-East Asia where 30% of the native peatland has been converted since 1990 (Miettinen et al. 2016). Land clearing for shifting agriculture or permanent conversion to cropland is typically achieved through fires, while other practices, such as drainage of peatland increase susceptibility of these landscapes to fires (Martin 2019). Fires emit \(NO_x\), \(PM_{2.5}\), \(NH_3\) and NMVOC, which are influenced by vegetation type and meteorology (Crutzen and Andreae 1990, Andreae and Merlet 2001, Akagi et al. 2011), and have been linked to hazardous levels of \(PM_{2.5}\) over the Amazon (Reddington et al. 2015) and in Southeast Asia (Kiely et al. 2019). Our review did not identify any studies that estimated primary \(PM_{2.5}\) and precursor emissions resulting from food-demand driven land-use change. Instead, we designed an approach based on GFED4 that reports emissions that are derived using satellite-derived burned area and vegetation-type specific emissions factors (van der Werf et al. 2017) and reported for 14 ecological regions that are aggregated to the following categories: savanna, grassland and shrubland, boreal forests, temperate forests, deforestation, peatland and agricultural waste burning.

We adopted the following method to derive \(PM_{2.5}\) and precursor emissions totals for land-use change. First, we extracted national-scale emissions from GFED4 for Asia, Africa and South America that experience large-scale deforestation (Carter et al. 2018) for the categories of savanna, grassland, shrubland, deforestation and peatland. Second, we extracted the extent of forest loss driven by wildfires, shifting agriculture and conversion for agriculture for the years 2012–2015 (World Resources Institute 2014). By combining forest loss data with GFED4, we identified emissions from shifting agriculture and permanent land-use change for agriculture. Finally, we identified the share of production for food versus non-food purposes based on the National Food Balance Sheets (FAO 2020b), and apply the fractional contribution of food to estimate emissions from land-use change. Similarly, GFED4 emissions for peatland were combined with the national-scale fractions of peatland fires on oil palm plantations (Miettinen et al. 2016, Petersen et al. 2016) and the fraction of oil palm diverted for food purposes (70%) (Lai et al. 2012).

#### 3.1.1.2. Fertilizer production

Agrochemicals including fertilizers, herbicides and pesticides have been widely used to maximize crop yields and for disease and pest management. The Haber–Bosch process, which was invented in the early 1900s, enabled the conversion of inert nitrogen to \(NH_3\) to produce nitrogen fertilizers, which has dramatically altered agricultural production (Sutton et al. 2011). Since 1960, croplands have received 300% more nitrogen from synthetic fertilizers than from natural biological nitrogen fixation, thus supporting nearly 48% of all crop production (Erisman et al. 2008b). Global fertilizer production increased by 520% between 1960 and 2014 (FAO 2020a), resulting in large on-site emissions of primary \(PM_{2.5}\) and \(NH_3\), as well as emissions of \(PM_{2.5}\), \(SO_2\), \(NO_x\) and NMVOC from embodied energy. Satellite data have identified 158 hotspots of \(NH_3\) emissions over fertilizer production sites in China, Ukraine, Iran and the United States (Van Damme et al. 2018).

EDGAR4.3.2 aggregate emissions from nitrogen fertilizer production into the ‘Industrial Processes and Product Use’ category (EEA 2016). While the emissions-factor approach can be replicated by combining emissions factors for the production of \(NH_3\) and other fertilizer types (EEA 2016) and scaled using agrochemical production statistics (FAO 2020a), it is challenging estimating emissions from embodied
Table 2. System-scale emissions inventory of the global food system. Annual emissions of primary PM$_{2.5}$ and secondary PM$_{2.5}$ precursors (NH$_3$, NO$_x$, SO$_2$, NMVOC) are reported by sector. Descriptions of the 15 emissions sectors, choice of global emissions database and year of reporting are also included. N/A refers to pollutants from sectors where emissions are expected but unreported by the emissions databases. Note that this inventory does not include emissions from the consumption stage (commercial cooking and residential cooking) given the challenges in delineating contributions to indoor/household and ambient PM$_{2.5}$ pollution. As a result, the presented emissions budgets are underestimated at the global scale.

| Stage       | Sector                      | Emissions database | Year | Primary PM$_{2.5}$ | NH$_3$ | NO$_x$ | SO$_2$ | NMVOC |
|-------------|-----------------------------|-------------------|------|-------------------|--------|--------|--------|-------|
| Pre-production | Land-use change            | GFED4             | 2012 | 14 000            | 1 400  | 1 450  | 870    | N/A   |
| Production  | Fertilizer production      | EXIOBASE3.3.17    | 2011 | 300               | 330    | 800    | 940    | 1 700  |
| Production  | On-farm energy use         | EDGAR4.3.2        | 2012 | 250               | 1      | 5 800  | 3 100  | 3 200  |
| Production  | Manure management          | EDGAR4.3.2        | 2012 | 339               | 16 600  | 325    | N/A    | 19 000 |
| Production  | Grazing                    | EDGAR4.3.2        | 2012 | 0                 | 8 400  | 0      | 0      | 0     |
| Production  | Fertilizer use             | EDGAR4.3.2        | 2012 | 0                 | 13 700 | 0      | 0      | 0     |
| Production  | Agricultural waste burning| EDGAR4.3.2        | 2012 | 6 800             | 7 400  | 2 100  | 360    | 3 800  |
| Production  | Other                      | Emissions-factor approach | 2012 | 100               | 50     | 16     | 0      | 1 400  |
| Post-production | Food industry             | EXIOBASE3.3.17    | 2012 | 140               | 14     | 1 400  | 870    | 30    |
| Post-production | Transportation            | Scaled from food industry emissions | 2012 | 240               | 23     | 950    | 1 500  | 60    |
| Consumption | Commercial cooking         | N/A               |      |                   |        |        |        |       |
| Consumption | Residential cooking        |                   |      |                   |        |        |        |       |
| Waste       | Open burning               | EXIOBASE3.3.17    | 2012 | 1400              | 160    | 530    | 529    | 3 200  |
| Waste       | Controlled disposal        |                  | 2012 | 0.3               | 520    | 9      | 0.7    | 140   |
energy use due to the lack of harmonized data on global fuel use for agrochemical production. Instead, we obtained data for emissions of primary PM$_{2.5}$, NO$_x$, SO$_2$, NH$_3$ and NMVOC from EXIOBASE3.17 that report emissions from mining of fertilizer minerals, and the production of nitrogen, phosphorus and other fertilizers (Merciai and Schmidt 2018). Emissions are reported for 44 countries and five regions outside those countries, which we distributed by population to gap-fill for the remaining countries. Finally, emissions were reduced proportionately to the percentage of agricultural commodity use for food versus non-food purposes derived from the National Food Balance Sheets (FAO 2020b). Our analysis excludes pesticide manufacturing as it typically occurs in a highly controlled environment to minimize direct health impacts, thus resulting in minimal PM$_{2.5}$-related emissions (EEA 2016).

3.1.2. Agricultural production

3.1.2.1. On-farm energy use

Energy is required on farms to power machinery, livestock housing and storage facilities. Diesel engines are widely used for powering tillage, planting, harvesting, irrigation, crop drying and transport operations. The input of energy to farms increased by 137% between 1961 and 2014 amounting to 2.6% of global energy use, while machinery and associated fuel use doubled (Pellegrini and Fernández 2018). In particular, large increases in machine stocks by 2400% in mainly irrigated countries including Bangladesh, China, India, Pakistan, Egypt and South Korea have been accompanied by a 50% increase in irrigated land. Of interest are emissions of primary PM$_{2.5}$, NO$_x$ and SO$_2$ resulting from fuel combustion. Several studies have examined contributions from off-road mobile sources, yet few have exclusively examined emissions from on-farm energy use. The use of agricultural machinery in China is linked to substantial emissions (250 Gg PM$_{2.5}$, 2.1 Tg NO$_x$, and 25 Gg SO$_2$), coinciding with peak agricultural activities in April, June and October (Wang et al 2016, Lang et al 2018). However, such explicit emissions accounting for on-farm energy use are unavailable at global scales, as is the lack of harmonized on-farm energy use data classified by technology and end-use. In the United States, diesel was the typical fuel used for on-farm machinery and related operations (38%) with smaller contributions from electricity (16%), gasoline (15%) and natural gas (10%) (Brown and Elliott 2005). Following the emissions-factor approach, we combined national-scale, fuel-specific on-farm energy use (FAO 2020a) and scale using Tier-1 emissions factors for agricultural energy use (EEA 2016) to report national-scale emissions for primary PM$_{2.5}$, NO$_x$ and SO$_2$. Emissions were reduced proportionally to the percentage of agricultural production for food versus non-food use based on the National Food Balance Sheets (FAO 2020b).

3.1.2.2. Livestock management

Human demand for animal-based food has quadrupled since 1961, with meat production increasing by 200% in Europe and North America, and significantly larger increases in Asia (1500%) and South America (530%) (FAO 2020a). Subsequently, manure-nitrogen production has increased by 520%, with regional contributions dominated by Asia (34%), Africa (17%) and South America (15%) (Zhang et al 2017a). Livestock systems are highly nitrogen inefficient, as a large fraction (45%–95%) of nitrogen from the feed is excreted as manure and urine (McQuilling and Adams 2015), which decomposes and is subsequently emitted as NH$_3$ through volatilization of nitrogen (Behera et al 2013). Livestock operations are also associated with primary PM$_{2.5}$ emissions from the movement of livestock within facilities (Ni et al 2009, Yang et al 2011), and trace emissions of NMVOC (Hobbs et al 2004) and SO$_2$ (Lim et al 2003).

Globally, NH$_3$ emissions from livestock management are attributed to the production of cattle (43%), goats and sheep (33%), swine (11%) and poultry (10%) (Zhang et al 2017a), and can occur at multiple stages in the livestock management system: from accumulated manure in housing, yard and storage facilities (31%–55%), land application for crop cultivation (23%–38%) and from livestock grazing (17%–37%) (Beusen et al 2008, Dämmgen and Hutchings 2008). The most important factors determining NH$_3$ emissions are the type of livestock, its age and the nitrogen content in the feed (Beusen et al 2008). Emissions from manure storage and handling depend on the surface area and bedding material. As a result, larger losses are observed in open housing with solid or slatted floors compared to cubicle houses, deep litter and closed manure storage systems (Dämmgen and Hutchings 2008). Emissions from manure application to crops are highly dependent on environmental conditions and application mode, with increased emissions positively correlated with higher temperatures, wind speeds and lower moisture content (Webb et al 2010).

NH$_3$ emissions from livestock rearing have received extensive attention in the development of emissions inventories and through multiple, targeted measurement campaigns in Europe and the United States (Slattery 2005). These efforts have resulted in detailed emissions factors that are differentiated by livestock type and manure management operation (housing, storage and handling, grazing and manure application to soils) (Batty et al 1994, EEA 2016), that are implemented in EDGAR4.3.2 (Crippa et al 2018). Additional approaches have been developed to better capture spatial and temporal heterogeneity in emissions. Semi-empirical models, such as the Farm Emissions Model fine-tune existing emissions factors by estimating NH$_3$ losses based on mass balances and mass transfer processes that are influenced by...
meteorology (McQuilling and Adams 2015). Process models have also been implemented to develop emissions inputs from manure management to AQMs (Deng et al 2015, Giltrap et al 2017). However, given the large data requirements to capture manure management systems and environmental conditions, and the need for calibrated models to capture region-specific variability, these approaches are yet to be scaled globally. Here, we obtain national-scale emissions of primary PM$_{2.5}$, NH$_3$ and NMVOC from EDGAR4.3.2 that are differentiated by livestock-type for the categories of manure handling and storage, manure application and grazing.

3.1.2.3. Fertilizer use

The application of synthetic fertilizers for crop cultivation is one of the most important land management practices to increase soil fertility and crop yields. Global nitrogen inputs to crops increased by 850% between 1960 and 2013 (Lu and Tian 2017) to meet the demand for food, animal feed and biofuels. Large regional variations exist in nitrogen use, ranging from 0.15–6 kg N ha$^{-1}$ in sub-Saharan Africa to 100–200 kg N ha$^{-1}$ in cropland in Asia (Lu and Tian 2017). Global NH$_3$ emissions increased from 1.9 to 16.7 Tg N between 1961 and 2010 (Behera et al 2012). Studies have resulted from the cultivation of rice, corn, wheat and soybeans (Xu et al 2019). Depending on the fertilizer type, amount and mode of application, and weather and soil conditions, 1%–64% of the applied nitrogen can volatilize as NH$_3$ (Sommer et al 2004, Balasubramanian et al 2017), thus representing a major financial loss to farmers (Pan et al 2016). Urea, which is the most commonly used fertilizer globally (Behera et al 2013), has a volatilization potential 22%–55% higher than other nitrogen forms (Goebes et al 2003, EEA 2016, Pan et al 2016).

Similar to livestock rearing, NH$_3$ emissions from fertilizer use are estimated using the emission-factor approach as in EDGAR based on fertilizer-type specific emission factors (Crippa et al 2018). However, this approach introduces large uncertainties as it does not capture the impact of crop management and the resulting spatial and temporal heterogeneity that has been identified at the farm scale (Sommer et al 2004, Nelson et al 2017, Ti et al 2019). Studies have addressed this challenge through the use of process models to characterize region-specific spatial and temporal variations in NH$_3$ emissions (Cooter et al 2012, Balasubramanian et al 2015, Xu et al 2019), and through the use of inverse models to improve seasonality in NH$_3$ emissions (Paulot et al 2014, Zhu et al 2015b). However, global deployment of the process model and inverse model approaches is limited due to scalability issues that result from limited regional-scale data for agricultural management, and resulting uncertainties that are often of the same order of magnitude as the emissions-factor approach (Schiferl et al 2016, Balasubramanian et al 2020). Similar to the livestock sector, we thus obtained national-scale NH$_3$ emissions from EDGAR4.3.2 that were proportionally adjusted for contributions for food versus non-food purposes using data from National Food Balance Sheets (FAO 2020b).

3.1.2.4. Agricultural waste burning

Open burning of agricultural waste is a low-cost way to dispose of crop residues left over after harvesting, land clearing and pest control (Crutzen and Andreae 1990, Akagi et al 2011). Annual agricultural waste burning increased by 150% between 1960 and 2015 (FAO 2020a), releasing large amounts of primary PM$_{2.5}$ (1.76 Tg), NH$_3$ (0.6 Tg), SO$_2$ (0.11 Tg), NO$_x$ (0.08 Tg) and NMVOC (0.11 Tg) (van der Werf et al 2017). Several studies have examined the impacts of agricultural waste burning at regional scales. In the United States, the burning of corn, cotton, bluegrass, rice, soybeans, sugarcane and wheat residues was linked to local increases in ambient PM$_{2.5}$ (Pouliot et al 2017). Similarly, the burning of rice, corn and wheat straw residue in China was linked to PM$_{2.5}$ emissions (Ni et al 2015), which may have been underestimated (Li et al 2017a). Burnt agricultural residue in India from managing rice (43%), wheat (26%), sugarcane (10%) and cereal residues (11%) (Ravindra et al 2019) has been linked to a 600% increase in ambient PM$_{2.5}$ during the harvest season (Jethva et al 2018). In Southeast Asia, rice straw burning dominated PM$_{2.5}$ emissions (95%–98%), largely driven by crop production in Indonesia (25%–39%), Vietnam (17%–30%), Myanmar (8%–19%) and Thailand (7%–16%). Emissions of primary PM$_{2.5}$, NH$_3$, NO$_x$, SO$_2$ and NMVOC from agricultural waste burning have been reported using the emissions-factor approach in both the GFED4 (van der Werf et al 2010) and EDGAR4.3.2 (Crippa et al 2018). Here, we obtain national-scale emissions from EDGAR4.3.2, which are proportionally adjusted for food versus non-food contributions by using data from the National Food Balance Sheets (FAO 2020b).

3.1.2.5. Other emissions

On-farm operations including plowing, tilling and harvesting, and on-farm handling and storage of agricultural products are typically associated with emissions of coarse PM that result from the attrition of dry plant particles, silica, biological species including molds, pollen, spores, bacteria, fungi and agrochemical residues. On-farm operations also emit primary PM$_{2.5}$ (Aneja et al 2009, van Grinsven et al 2013), with contributions ranging from 2%–5% of the total anthropogenic, primary PM$_{2.5}$ emissions in Europe (Erisman et al 2008a, Oenema et al 2012) and Canada (Pattey and Qiu 2012) to 15% in the United States (Penfold et al 2005). Crops also naturally emit NMVOC, including isoprene, monoterpenes and sesquiterpenes, among 50 other identified...
species as a part of normal growth (Lamb et al 1993, König et al 1995, Laothawornkitkul et al 2009) or as a defense mechanism that can be triggered during harvesting (Guenther et al 2000). Miscellaneous sources include emissions from pesticides and NH₃ emissions from treated straw that is used as ruminant feed. Here, we follow the EDGAR4.3.2 methodology to estimate on-farm primary PM$_{2.5}$ emissions and NMVOC emissions from standing crops by combining national-scale crop production data (FAO 2020a) with emissions factors (EEA 2016). We exclude emissions from pesticide application and treated straw as they are assumed to be negligible. These estimates are adjusted for food demand using data from the National Food Balance Sheets (FAO 2020b).

3.1.3. Post-production
3.1.3.1. Food industry
Food and beverage manufacturing (here, the ‘food industry’) includes industrial manufacturing of food ingredients and products that are processed and packaged typically for retail. The global food industry annually consumes 200 EJ energy (Ladha-Sabur et al 2019), accounting for 4% of the industrial energy consumption in OECD (Organisation for Economic Co-operation and Development) countries and 2% in non-OECD countries (EIA 2016). The reporting of sub-national-scale energy embodied in the food industry is fragmented and only for select commodities (Ladha-Sabur et al 2019). The industrial processing of food products emits primary PM$_{2.5}$, NH$_3$, NO$_x$, SO$_2$ and NMVOC (US EPA 1995) as a result of embodied energy use and on-site operations. While the emissions-factor approach can be implemented to estimate these emissions, the lack of harmonized data on national-scale fuel and technology used to power the food industry, and how food commodities are produced, limit these efforts. Here, we obtain data for emissions of primary PM$_{2.5}$, NH$_3$, NO$_x$, SO$_2$ and NMVOC from EXIOBASE3.3.17 for the production and processing of meat from cattle, poultry and pigs, vegetable oils and fats, dairy products, processed rice, sugar refining, beverages, seafood products and miscellaneous food commodities (Merciai and Schmidt 2016). These emissions are reported for 43 countries and for five regions for all other countries, which we distributed proportionally to the national population to gap-fill data.

3.1.3.2. Retail and distribution
Energy use in food retail is driven by business size, nature of products sold and use of equipment for on-site food preparation and preservation (Vermeulen et al 2012, Ladha-Sabur et al 2019). Commercial refrigeration is highly energy-intensive, accounting for 15% of global electricity consumption (James and James 2010). We identified only one study (hereafter DEFRA report) that reported primary PM$_{2.5}$ and secondary PM$_{2.5}$ precursor emissions from food retail and distribution. The report provided relative emissions contributions for the food industry, retail and distribution, and food transportation, but was limited to the United Kingdom (Smith et al 2005). Given the lack of such data at the global scale, we combined the relative contributions from the DEFRA report with the national-scale food industry emissions derived from EXIOBASE3.3.17 to estimate national-scale food retail and distribution emissions. As a caveat, the United Kingdom is a high-income country. Thus, our approach will result in higher magnitudes of emissions than expected at the global-scale and be reflective of supply chain management trends that low-income countries may adopt in the future.

3.1.3.3. Transportation
The transportation of food or ‘food miles,’ is a popular albeit often misapplied, indicator to assess the sustainability of food commodities (Schnell 2013). While the impact of food miles on greenhouse gas (GHG) emissions (Pirog et al 2001, Weber and Matthews 2008) and along supply chains of specific commodities (Brodlt et al 2013, Brunori et al 2016, Schmitt et al 2016) have been studied, the focus on air pollutant emissions is rather limited. We identified only one study reporting PM$_{2.5}$ emissions from food miles, which was limited to the United Kingdom (Smith et al 2005). Transportation modes have a significant impact on emissions, with lower reported emissions per km-tonne for food moved by ship and rail in comparison to cars and trucks. While food commodity flows by transportation modes are reported for Europe (Eurostat 2019) and the United States (Federal Highway Administration 2014), limited data coverage on transportation choice and fuel use at the global scale limits the estimation of primary PM$_{2.5}$ and secondary PM$_{2.5}$ precursor emissions. Freight transport of goods including food commodities has been linked to PM$_{2.5}$-related health impacts resulting from emissions of PM$_{2.5}$ and NO$_x$ (Liu et al 2019). It is imperative to establish the global-scale air quality impacts of transportation occurring as a result of food trade (Dalín and Rodríguez-Iturbe 2016), given that 25% of the food produced globally is traded (O dorico et al 2014). Similar to the retail and distribution sectors, we combine relative contributions of food transportation from the DEFRA report with national-scale food industry emissions estimates, without accounting for miles from retail to home.

3.1.4. Food preparation and consumption sectors
3.1.4.1. Commercial cooking
Several studies have examined the contribution of commercial cooking to ambient PM$_{2.5}$ pollution in urban settings (Robinson et al 2006, 2018, Gysel et al
2018), through emissions of ultrafine particles (PM with diameter <0.1 μm) that are retained longer in the lungs and cause more pulmonary infections than PM$_{2.5}$ (Schraufnagel 2020), and NMVOC in the form of $n$-alkanes, furans, lactones, polycyclic aromatic hydrocarbons and cholesterol (Rogge et al 1991). Commercial cooking often elevates PM$_{2.5}$, especially ultrafine fractions (PM$_{2.5}$ ≤ 0.1 μm) several orders of magnitude higher compared to the urban background and to larger extents than congested roadways (Robinson et al 2018) and smoking (Nasir and Colbeck 2013). These emissions are influenced by practices including cooking style, the temperature, duration of cooking and type of cooking oil (Abdullahi et al 2013, Torkmahalleh et al 2017). Commercial cooking impacts not only in-house workers, but elevates ambient PM$_{2.5}$ concentrations (50%–300%) and drives spatial patterns in PM$_{2.5}$ exposure in neighboring urban areas (Robinson et al 2018, Saha et al 2019), with disparate socio-economic impacts given the demographics of the population living in proximity to restaurants (Shah et al 2020).

Only the United States reports commercial cooking emissions that are classified by the equipment type and amount of food cooked (Roe et al 2004, US EPA 2018). Commercial cooking accounts for 1% of national PM$_{2.5}$ emissions resulting from underfired-char broilers (78%), conveyoziered charbroilers (10%) and flat griddle frying (12%) (Roe et al 2004). Commercial food establishments account for a large fraction of the energy consumption (28%–34%) in the United States (Todd 2017), and this fraction is increasing globally (Fryar et al 2018). The lack of similar emissions reporting for other countries limits efforts to develop a global emissions inventory. Here, we do not quantify commercial cooking emissions, given data constraints and endemic challenges in delineating indoor-outdoor emissions contributions. However, given that this sector accounts for 1% of the PM$_{2.5}$ national emissions and an increasing shift towards consumption of food from commercial cooking, this source may be of increasing importance for urban air pollution, and should be revisited.

3.1.4.2. Household cooking

Much of the focus on cooking and PM$_{2.5}$ pollution has been on household air pollution resulting from solid fuel use, which is a major health risk in developing countries (Smith and Pillarisetti 2017, Goldemberg et al 2018). In 2017, 3.6 billion people, primarily in South Asia, East Asia and sub-Saharan Africa, were exposed to elevated household PM$_{2.5}$ concentrations resulting from the use of solid fuels, such as wood, charcoal, coal and other biomass (Health Effects Institute 2019). Similar to commercial cooking, household cooking emits primary PM$_{2.5}$, NMVOC and trace levels of NO$_x$ and SO$_2$, that are dependent on fuel type (Sidhu et al 2017) and cooking practices, such as food and oil type, cooking temperature and duration, type and efficiency of cooking appliance, and indoor ventilation (Rehfuess et al 2011, Hu et al 2012).

A large body of the literature has examined emissions from solid fuel use in various settings. Example studies include laboratory measurements (Rodewal et al 2009, Preble et al 2014, Shen et al 2017), field measurements from uncontrolled in-home stoves in India (Pandey et al 2017, Mengwani et al 2019), China (Li et al 2007, Jiang and Bell 2008, Shen et al 2015), Ethiopia (Mamuye et al 2018), Ghana (Zhou et al 2011, Dickinson et al 2015), sub-Saharan Africa (Tumwesige et al 2017) and Mexico, inter-country comparisons (Rose Eilenberg et al 2018, Johnson et al 2019) and comparative emissions reductions from improved cookstoves (Coffey et al 2017, Sonarkar and Chaurasia 2019). The reported PM$_{2.5}$ emissions factors (g MJ$^{-1}$) are highly variable (0.01–1.5), with lower emissions rates observed for electric and gas stoves, and nearly an order of magnitude higher for natural-draft and traditional cookstoves fueled by charcoal, wood and residue (0.06–1.8) (Arora and Jain 2016). Average emissions factors (g kg$^{-1}$) for primary organic aerosols, SO$_2$, NMVOC and NO$_x$ have been compiled for mud stoves (5.7, 0.3, 2.7 and 1.0 respectively), conventional wood stoves (3.9, 0.2, 23.6 and 2.8), wood boilers (1.5, 0.3, 14 and 1.2) and coal-burning stoves (0.8, 0.2, 0.5 and 2.2) (Bond et al 2013). Average emission rates for outdoor cooking to model personal exposure were found to be substantially higher than for indoor cooking (Edwards et al 2017). Hu et al (2012) compiled a PM$_{2.5}$ emissions database for residential environments in the United States and identified lower emissions rates for microwave and oven use (0.64–0.7 mg h$^{-1}$) and 200%–300% higher for frying irrespective of oil type.

EDGAR4.3.2 does not account for ambient PM$_{2.5}$ and precursor emissions from household cooking. These contributions, which are specific to ambient air pollution, are instead reported by the GAINS emissions model based on the methodology by Chafe et al (2014). Household fuel use for cooking and heating is a significant contributor to anthropogenic PM$_{2.5}$ emissions, ranging from 20%–55% globally (Tao et al 2016, Perez et al 2019). Here, we do not further compile a global emissions inventory for cooking. There are multiple opportunities to develop further research on the impacts of household cooking on PM$_{2.5}$-attributable premature deaths. Topics of interest to the broader conversation of the sustainability of food systems include (a) cookstove technologies (Arora and Jain 2016) and the impacts on PM$_{2.5}$-attributable health damage (Grieshop et al 2011), (b) socio-economic and air quality impacts of carbon-financing schemes and national-scale fuel
Figure 2. Global emissions of primary PM$_{2.5}$, NH$_3$, NO$_x$, SO$_2$ and NMVOC. Relative contributions by emissions sectors and grouped by stage in the food system: pre-production (orange), production (green), post-production (blue) and waste (yellow). Emissions from the consumption stage are not included. Percentage contribution of emissions from the global food system relative to total anthropogenic contributions are provided to the right of the bars.

3.1.5. End-of-life disposal practices

Food loss and waste occur at all stages of the food supply chain (Parfitt et al 2010). Food losses of >40% are common in developing countries during the production and post-harvest stages, typically through agricultural waste burning due to inefficient technologies and poor infrastructure. Food waste of >40% at the retail and consumer stage is typical in developed countries and nearly equals the net food production in sub-Saharan Africa (Lipinski et al 2013). Household loss is the most important source of food waste with large per-capita variation, ranging from 6–11 kg yr$^{-1}$ in sub-Saharan Africa to 95–115 kg yr$^{-1}$ in Europe and North America (Lipinski et al 2013, Xue et al 2017). Waste can be disposed of through open burning or integrated within municipal solid waste systems in the form of controlled incineration, landfilling or composting. Thus, emissions of primary PM$_{2.5}$ and secondary PM$_{2.5}$ precursors are a function of both waste quantity and mode of food disposal. In the only study identified, Grizzetti et al (2013) estimated that food waste management emitted 0.21 Tg NH$_3$ and 0.086 Tg NO$_x$ for Europe. Few studies have provided emissions totals of trace gases and PM$_{2.5}$ from the open burning of domestic waste at national (India: Sharma et al 2019) and global scales (Wiedinmyer et al 2014). However, this analysis is not exclusive to food waste. Here, we derive emissions of primary PM$_{2.5}$, NH$_3$, NO$_x$, SO$_2$ and NMVOC for 43 countries from EXIOBASE3.3.17, and gap-fill data for other countries by combining national-scale solid waste data that are classified by waste management method (World Bank 2018a) and technology-specific emissions factors (EEA 2016).

3.2. Global emissions inventories

We present national-scale emissions inventories of primary PM$_{2.5}$ and secondary PM$_{2.5}$ precursors from the global food system, reported for the year 2015 or the most recent year of available data, following the methods we describe at the sector-scale in section 3.1. Global emissions totals of primary PM$_{2.5}$ and secondary PM$_{2.5}$ precursors are shown in table 2 with fractional sector contributions shown in figure 2. Figures 3 and 4 show national emissions totals and regional-scale fractional sector contributions, respectively. Overall, we find that the global food system is a major contributor to the anthropogenic emissions of primary PM$_{2.5}$ (58%), NH$_3$ (72%), SO$_2$ (9%) and NMVOC (19%) in comparison to total anthropogenic emissions reported in EDGAR4.3.2 (Crippa et al 2018). We estimate that the global food system emits 24 Tg primary PM$_{2.5}$, driven by fires for land-use change (60%), agricultural waste burning (28%) and open burning of food waste (6%). The dominant emission sources of primary PM$_{2.5}$ vary regionally. Land-use change was identified as the predominant source in South America, Africa and Asia, while crop management...
and on-farm energy use dominate primary PM$_{2.5}$ emissions in North America and Eastern Europe, and China and Russia, respectively.

Global NH$_3$ emissions (42 Tg NH$_3$) largely result from livestock manure management (40%), grazing (20%) and synthetic fertilizer use (33%), with large variations in relative regional contributions. Fertilizer use is also a dominant contributor to NH$_3$ emissions in Asia and North America (40%–45%) in contrast to smaller contributions in Africa (<10%), where the slower adoption of nitrogen fertilizers and inefficient manure handling practices (Ndambi et al 2019) result in more than 50% contributions from livestock management. Of the 32 Tg NMVOC emitted from the food system, the dominant contributors included manure management (58%) and agricultural waste burning (12%). Smaller emissions totals were estimated for SO$_2$ (9 Tg) and NO$_x$ (16 Tg), which are typically a result of combustion. SO$_2$ was linked to on-farm energy use (35%), post processing of food (30%) and open burning (15%), with similar trends for NO$_x$ (35%, 30% and 6%, respectively).

4. PM$_{2.5}$ exposure and PM$_{2.5}$-attributable deaths from the food system

We describe the causal pathway of emission impacts on ambient PM$_{2.5}$ concentrations and PM$_{2.5}$-attributable premature deaths in section 4.1, summarize studies that report PM$_{2.5}$-attributable premature deaths from sectors within the global food system to develop an overall estimate of PM$_{2.5}$-attributable premature deaths in section 4.2, and discuss uncertainties in section 4.3.

4.1. Connecting the emissions—PM$_{2.5}$ exposure—premature mortality pathways

Ambient PM$_{2.5}$ concentrations are a result of precursor emissions, and are impacted by transport, chemistry and removal processes in the atmosphere. Of key importance to the discussion here are the emissions of NH$_3$, 72% of which is emitted from the food system (section 3.2). As the most dominant alkaline component in the atmosphere, NH$_3$ neutralizes acids formed from atmospheric
Figure 4. Region- and pollutant-specific emissions contributions from each stage over the life-cycle of the global food system. Emissions are grouped as follows: pre-production (orange) and production (green) that are further classified as fertilizer use, manure management and grazing, and aggregated emissions that include agricultural waste burning, on-farm energy use and other emissions (standing crop emissions and on-site handling of agricultural commodities), post-production (blue) and waste (yellow). Emissions from consumption are excluded in the analysis.

Oxidation of precursor gases, such as SO$_2$ and NO$_x$, and organic acids to form PM$_{2.5}$ (Behera et al 2013). The concentration of ambient PM$_{2.5}$ and chemical partitioning, especially as PM-nitrate, is driven by the relative abundance of NH$_3$ and acids formed from precursors, such as SO$_2$ and NO$_x$ in the atmosphere, thermodynamically driven by environmental conditions (Seinfeld and Pandis 2016), and thus can vary regionally and seasonally (Holt et al 2015, Weagle et al 2018). While PM$_{2.5}$ concentrations are more sensitive to the availability of NO$_x$ in regions of high NH$_3$ concentrations (Langridge et al 2012), such as in India (Kharol et al 2013) and China (Lin et al 2020), NH$_3$ is still a major contributor to the overall PM$_{2.5}$ abundance (Wärner et al 2017).

Despite air quality regulations in most regions of the world, global annual average ambient PM$_{2.5}$ concentrations are still 300% higher than the World Health Organization’s recommended healthy air guideline of 10 $\mu$g m$^{-3}$ (van Donkelaar et al 2016), 92% of the global population lives in countries in Africa, Southeast and East Asia, and the Middle East, where exposure exceeds 10 $\mu$g m$^{-3}$ (Health Effects Institute 2019), and has significantly increased since 1998 (Li et al 2017b). Studies have identified chronic health risks even in regions of relatively clean air, where PM$_{2.5}$ exposure is lower (Shi et al 2016). Ambient PM$_{2.5}$ has been linked to reduced global life expectancy (Apte et al 2018), which results from a wide range of health impacts including ischemic heart disease, chronic obstructive pulmonary disease, cerebrovascular disease, lung cancer and non-communicable diseases including lower respiratory tract disease (West et al 2016, Pope et al 2019). The extent of health damage varies as a result of ambient PM$_{2.5}$ concentration, length of exposure and demographics especially for elderly and vulnerable populations as demonstrated by toxicological, short-term epidemiological and large-scale cohort studies (Shiraiwa et al 2017). The impact of PM$_{2.5}$ on mortality has been represented through integrated exposure-response (IER) functions that are developed based on a comprehensive body of cohort and population studies (Pope et al 2019).

To date, the analysis of emissions contributions to PM$_{2.5}$-attributable deaths has been limited to economic sectors, such as energy and transport (Lelieveld et al 2015, 2019, Silva et al 2016) with a few select studies examining agriculture (Bauer et al 2016, Pozzer et al 2017, Giannadaki et al 2018).
The typical approach is to sequentially: (a) generate emissions inputs to AQMs, (b) develop spatially resolved AQM predictions of ambient PM\textsubscript{2.5} concentrations, (c) estimate population-weighted PM\textsubscript{2.5} exposure and (d) finally scale PM\textsubscript{2.5} exposure using IER functions to estimate PM\textsubscript{2.5}-attributable premature deaths. The AQM framework has been implemented using two approaches (Conibear et al.
2018). In the ‘zeroed out’ approach, emissions from a sector of interest are zeroed or reduced and the resulting PM\textsubscript{2.5} deaths are attributed as source contributions. Alternatively, in the ‘attribution’ approach, sector-specific mortality is estimated in proportion to the fraction of the sectoral contribution to PM\textsubscript{2.5} concentrations, either by examining emissions contributions or in models that ‘tag’ PM\textsubscript{2.5} concentrations as marginal changes in emissions. Given that emissions totals in the two approaches differ and due to the nonlinear emissions-PM\textsubscript{2.5} exposure responses, estimates of premature mortality can vary, especially in populated regions (Conibear et al.
2018).

The analysis of health damage beyond broad economic sectors has been limited due to the large computational, data and resource requirements when using AQMs. Advances in high-performance computing, the use of alternative statistical approaches and the development of other models, such as reduced complexity models (RCMs) have enabled AQM assessments at high spatial resolution and for multiple scenarios. RCMs use simplified representations of atmospheric processes with variable grid sizes and leverage outputs from an existing AQM simulation to predict marginal changes in ambient PM\textsubscript{2.5} concentrations at high spatial resolution in response to marginal changes in precursor PM\textsubscript{2.5} emissions, with reduced computational times (Tessum et al.
2017). RCMs have been widely implemented to study contributions of emissions to PM\textsubscript{2.5}-attributable premature deaths from various economic sectors at high spatial scales (Goodkind et al.
2019), delineate contributions at the emissions sector and pollutant scales to inform mitigation efforts (Thakrar et al.
2020) and to monetize damage (Heo et al.
2016, Gilmore et al.
2019). These applications are currently limited to the United States, given the current constraints on the spatial formulations of RCMs.

4.2. Global food system linked to significant PM\textsubscript{2.5}-attributable premature deaths

4.2.1. Summary of studies discussing the impact on ambient PM\textsubscript{2.5}-attributable premature deaths

Given the large contribution of the global food system to primary PM\textsubscript{2.5} and NH\textsubscript{3} emissions, and the central role of NH\textsubscript{3} in the formation of secondary PM\textsubscript{2.5}, we identify the lack of a system-scale analysis on the contribution of the global food system to PM\textsubscript{2.5}-attributable premature deaths as a key literature gap. Here, we briefly discuss AQM studies that link emissions from different stages and emissions sectors within, but not exclusive to the food system to ambient PM\textsubscript{2.5}-attributable premature deaths. Key findings are summarized in table 3, which highlights differences in the approaches used by the listed studies in terms of spatial extent of analysis, choice of emission inventories and AQM configurations, and the reporting of health damage.

Much of the focus on the impacts of the global food system on air quality has been on agricultural production. Emissions from agricultural production contribute to about 20% of PM\textsubscript{2.5} deaths worldwide (Lelieveld et al.
2015), with larger contributions in China, the United States and Europe (45%–55%) and smaller contributions in India and Africa (3%–15%) (Bauer et al.
2016, Guo et al.
2018, Crippa et al.
2019). A recent integrated health and environmental assessment by Malley et al.
(2021) linked global agricultural production to 537,000 PM\textsubscript{2.5}-related deaths. Notably, a 100% reduction in these emissions would reduce 800,000 (95% confidence interval (95% CI): 420,000–980,000) global, annual PM\textsubscript{2.5}-attributable premature deaths (Pozzer et al.
2017). Achievable health benefits were identified to be the largest for Europe and North America (70%–80%) where significant reductions in NO\textsubscript{x} and SO\textsubscript{2} emissions have already been achieved and PM\textsubscript{2.5} formation is highly sensitive to NH\textsubscript{3} emissions (Pozzer et al.
2017, Giannadaki et al.
2018). These responses were smaller in Asia (3%–25%), where PM\textsubscript{2.5} and PM-nitrate formation are sensitive to NO\textsubscript{x} emissions (Bauer et al.
2016, Giannadaki et al.
2018). Goodkind et al.
(2019) estimated that NH\textsubscript{3} emissions from the United States agriculture resulted in 16,000 excess deaths and economic damage of 40,000 USD. However, large spatial variations (∼500%) were reported for this marginal damage. The morbidity and mortality costs of 1 kg NH\textsubscript{3} emitted into the atmosphere showed large spatial variability (0.1–73 USD) and were valued to be much larger than the marginal damage that results from emissions of SO\textsubscript{2} (0.2–12 USD) and NO\textsubscript{x} (0.02–2 USD) that have been the historic focus for PM\textsubscript{2.5} regulation (Muller and Mendelsohn
2010, Gilmore et al.
2019). Overall, these findings suggest that air pollution regulations should consider regional-scale impacts of NH\textsubscript{3} emission reductions that are expected to provide the largest gains in Europe and North America, consistent with Pinder et al.
(2007) and Megaritis et al.
(2013).

Landscape fires (wildfires, prescribed burning and biomass burning but not limited to the global food system) have been linked to 330,000 (interquartile range: 260,000–600,000) excess deaths (Johnston et al.
2012). Open biomass burning is a significant contributor to PM\textsubscript{2.5}-excess deaths in China (1 million (95% CI: 840,000–1.3 million)), India (990,000 (95% CI: 660,000–1.35 million)) (Reddington et al.
2019) and Africa (780,000 (95% CI: 760,000–800,000)) (Bauer et al.
2019). However, these estimates are not delineated for contributions specific to the pre-production (land-use change),
Table 3. List of studies reporting PM$_{2.5}$-premature mortality estimates for sectors relevant but not exclusive to the global food system. Of the 320 studies, data sets and reports synthesized in this review, only 19 were identified that followed the causal chain of emissions-PM$_{2.5}$ exposure-premature mortality for sectors relevant to the global food system. These are listed in chronological order with a focus on the geographic scale of analysis, emissions sector and pollutants of interest, air quality model configuration including the name of the air quality model, emissions database, and horizontal grid resolution, and findings from the studies in terms of PM$_{2.5}$-excess deaths and economic damage. An important caveat is that the excess death estimates are based on different IER functions and are not adjusted for contributions of or for the global food system, given that the scope of all but three of the reported studies (marked with *) are not focused on the food system. Reported estimates could thus also include contributions resulting from land-use change for urbanization, mining, timber production and the production of non-food agricultural commodities, such as fiber and biofuels. Air quality and emissions model acronyms are defined alphabetically in the footnote. 

| Study                  | Region           | Sector                         | Pollutants            | Approach       | Air quality model (AQM) configuration | Premature mortality |
|------------------------|------------------|--------------------------------|-----------------------|----------------|--------------------------------------|---------------------|
| Johnston *et al* (2012)| Global           | Landscape fires                | PM$_{2.5}$, NH$_3$, NO$_x$, SO$_2$, NMVOC | Zero-out       | GEOS-Chem GFED                       | 2° × 2.5° 1997–2006 340 000 (260 000–600 000) |
| Paulot *et al* (2014)  | United States    | Food export *                  | NH$_3$, NO$_x$       | Zero-out       | GEOS-Chem MASAGE                      | 2° × 2.5° 2005 5100 (3400–6700) 36 billion |
| Lelieveld *et al* (2015)| Global           | Production                      | PM$_{2.5}$, NH$_3$, NO$_x$, SO$_2$, NMVOC | Zero-out       | ECHAM EDGAR                          | 1.1° × 1.1° 2010 660 000 |
| Reddington *et al* (2015)| South America    | Land-use change                | PM$_{2.5}$, NH$_3$, NO$_x$, SO$_2$, NMVOC | Zero-out       | GLOMAP MACCity + GFED                 | 2.8° × 2.8° 2002–2011 2900 (1000–4700) |
| Crippa *et al* (2016)  | Southeast Asia   | Land-use change                | PM$_{2.5}$, NH$_3$, NO$_x$, SO$_2$, NMVOC | Zero-out       | WRF-Chem EDGAR + FINN                 | 10 km × 10 km 2015 12 000 (6100–17 000) |
| Heo *et al* (2016)     | United States    | Production                     | PM$_{2.5}$, NH$_3$, NO$_x$, SO$_2$, NMVOC | Attribution    | EASIUR NEI                           | 36 km × 36 km 2005 110 billion |
| Kodros *et al* (2016)  | Global           | Domestic waste burning         | Primary PM$_{2.5}$   | Zero-out, attribution | GEOS-Chem EDGAR + waste burning inventory | 2° × 2.5°, 0.5° × 0.66° (Asia) 2010 191 000 (150 000–220 000) |
| Lal *et al* (2016)     | Agra, India      | Domestic waste burning         | Primary PM$_{2.5}$   | Attribution    | AERMOD Solid waste, dung burning inventory | N/A 2015 700 (400–1050) |
| Li *et al* (2017)      | China            | Agricultural waste burning     | PM$_{2.5}$, NH$_3$, NO$_x$, SO$_2$, NMVOC | Zero-out       | Box model Solid waste, dung burning inventory | Measurements N/A 2012 7800 (3200–12 000) |

(Continued.)
Table 3. (Continued.)

| Study | Region | Sector | Pollutants | Approach | Spatial resolution | Year | Year | Excess deaths | Costs (USD) |
|-------|--------|--------|------------|----------|-------------------|------|------|---------------|-------------|
| Pozzer et al (2017) | North America, Europe, Asia | Production | PM$_{2.5}$, NH$_3$, NO$_x$, SO$_2$, NMVOC | Zero-out | ECHAM EDGAR 1.1 | 2012 | 2012 | 407 billion |
| Giannadaki et al (2018) | North America, Europe, Asia | Production | PM$_{2.5}$, NH$_3$, NO$_x$, SO$_2$, NMVOC | Zero-out | HTAP + FINN | 2010 | 2010 | 130,000 (19,000–200,000) |
| Pozzer et al (2017) | China | Crop production | PM$_{2.5}$, NH$_3$, NO$_x$, SO$_2$, NMVOC | Zero-out | CMAQ | 27 km x 27 km | 2010 | 27 km x 27 km | 180,000 (180,000–200,000) |
| Pozzer et al (2017) | China | Livestock rearing | PM$_{2.5}$, NH$_3$, NO$_x$, SO$_2$, NMVOC | Zero-out | TM5-FASST | 1° x 1° | 2010 | 1° x 1° | 180,000 (180,000–200,000) |
| Gu et al (2018) | China | Crop production | PM$_{2.5}$, NH$_3$, NO$_x$, SO$_2$, NMVOC | Attribution | InMAP | 1 km x 1 km grid | 2011 | 1 km x 1 km grid | 180,000 (180,000–200,000) |
| Gu et al (2018) | China | Livestock rearing | PM$_{2.5}$, NH$_3$, NO$_x$, SO$_2$, NMVOC | Attribution | InMAP | 1 km x 1 km grid | 2014 | 1 km x 1 km grid | 39 billion |
| Crippa et al (2019) | Global | Livestock rearing | PM$_{2.5}$, NH$_3$, NO$_x$, SO$_2$, NMVOC | Attribution | EDGAR-HTAP | 0.1° x 0.1° | 2010 | 0.1° x 0.1° | 359,000 (228,000–513,000) |
| Goodkind et al (2019) | United States | Production | PM$_{2.5}$, NH$_3$, NO$_x$, SO$_2$, NMVOC | Attribution | InMAP | 1 km x 1 km grid | 2011 | 1 km x 1 km grid | 4300 |
| Reddington et al (2019) | South and East Asia | Biomass burning | PM$_{2.5}$, NH$_3$, NO$_x$, SO$_2$, NMVOC | Zero-out | WRF-Chem | 2.5° x 2.5° | 2014 | 2.5° x 2.5° | 39 billion |
| Hill et al (2019) | United States | Production | PM$_{2.5}$, NH$_3$, NO$_x$, SO$_2$, NMVOC | Attribution | CMIP | 1 km x 1 km grid | 2014 | 1 km x 1 km grid | 15,900 |
| Domingo et al (2020) | Global | Production | PM$_{2.5}$, NH$_3$, NO$_x$, SO$_2$, NMVOC | Attribution | GEOS-Chem | 2.5° x 2.5° | 2014–2018 | 2.5° x 2.5° | 527,500–536,800 |

Three studies listed here specifically account for contributions related to the global food system. Estimates for excess deaths for the other studies are not exclusive to the global food system.

Abbreviations: AERMOD (AMS/EPA Regulatory Model), CMAQ (Community Multiscale Air Quality), CMIP (Coupled Model Intercomparison Project), EASIUR (Estimating Air pollution Social Impact Using Regression), ECHAM (Climate Model), EDGAR (Emission Database for Global Atmospheric Research), FINN (Fire INventory from NCAR), HTAP (Hemispheric Transport of Air Pollution Inventory), GEOS-Chem (Goddard Earth Observing System—Chem), GFED (Global Fire Emissions Database), GISS (Goddard Institute for Space Studies General Circulation Model), GLOMAP (Global Model of Aerosol Processes), InMAP (Intervention Model for Air Pollution), MACCity (Monitoring Atmospheric Composition and Climate/CityZEN EU projects emissions data set), MASAGE (Magnitude And Seasonality of Agricultural Emissions), NEI (National Emissions Inventory), TM5-FASST (Tracer Model version 5—FAst Scenario Screening Tool), WRF-Chem (Weather Research and Forecasting model coupled with Chemistry).
production (agricultural waste burning) and waste (open burning of food waste) stages in the global food system. Several studies have explored the impact of land-use change on emissions but are limited to a few regions. Ambient PM$_{2.5}$ spikes have been reported in Singapore in August–October ($>5 \mu g \text{m}^{-3}$) (Reddington et al 2014), and annually in Sumatra and Borneo ($>120 \mu g \text{m}^{-3}$) (Kiely et al 2019). The observed increases in ambient PM$_{2.5}$ were linked to oil palm expansion in peatlands and attributed to 12 000 excess annual deaths in Equatorial Asia (Crippa et al 2016). Similarly, deforestation fires in South America were linked to 1100–4700 premature deaths (Reddington et al 2015). Open burning of domestic waste, which includes commodities in addition to food, has been linked to 190 000 (95% CI: 150 000–270 000) global, annual PM$_{2.5}$-excess deaths (Kodros et al 2016), and accounts for 6% of the total PM$_{2.5}$ exposure in India (Rooney et al 2019) and 16% in China (Gu et al 2018).

In addition to these sectors, food export in the United States was linked to an average increase in PM$_{2.5}$ exposure by 0.36 $\mu g \text{m}^{-3}$, mostly attributed to NH$_3$ emissions, and resulted in 36 billion USD damage in 2006, which was equivalent to 50% of the food export value (Paulot and Jacob 2014). Hill et al (2019) estimated that maize cultivation, which accounts for 95% of all feed grain production in the United States, was linked to 4300 PM$_{2.5}$-attributed premature deaths. The resulting economic damage valued at 39 billion USD in 2017 exceeded the monetized damage as a result of GHG emissions, and in 40% of the maize growing states the combined PM$_{2.5}$ and GHG economic damage exceeded the market value, indicating large negative externality costs.

4.2.2. Estimate of ambient PM$_{2.5}$-attributable premature deaths resulting from the global food system
The studies summarized in section 4.2.1 collectively highlight the large PM$_{2.5}$-attributable premature deaths from sectors related to but not exclusive to the global food system. Here, we develop the first estimate, to our knowledge, of annual PM$_{2.5}$-attributable premature deaths from the global food system, as summarized in table 4. For the agricultural production stage, we adjust the median PM$_{2.5}$-attributable deaths from agricultural production reported by Pozzer et al (2017) with the fraction of global crop area devoted to food production to estimate 750 000 excess PM$_{2.5}$ deaths from food production. Similarly, for the waste stage, we adjust estimates by Kodros et al (2016) with the fraction of domestic waste that is composed of food (40%) to conservatively estimate 76 000 median excess PM$_{2.5}$ deaths. We derive estimates for food-demand-driven land-use change using findings for landscape fires by Johnston et al (2012), by first deducting PM$_{2.5}$-death contributions from fires resulting from open waste burning (Kodros et al 2016) and then further deducting contributions resulting from natural wildfires (23%) and non-agricultural commodity land-use change (30% of prescribed burning) (World Resources Institute 2014), resulting in an average estimate of 70 000 excess PM$_{2.5}$ deaths. We ensure no double counting of deaths occurred by conforming to the system boundaries that were used to describe stages in the food system and by excluding open waste burning, wildfires and non-food commodity land-use change from landscape fires.

Overall, by adding these estimates, we identify that 890 000 median excess deaths can be attributed to the global food system, 84% being a result of emissions from agricultural production. This order of magnitude estimate, developed based on studies with different approaches and IER functions (see table 4), is equivalent to 23% of the overall 3.9 million PM$_{2.5}$-attributable deaths in the Global Burden of Disease Study 2015 (IHME 2020), and is similar or higher in comparison to global contributions from natural sources (18%), power generation (14%) and transportation (5%) (Lelieveld et al 2015, Crippa et al 2019). Our estimates are higher than the PM$_{2.5}$-related deaths reported by Malley et al (2021), as our accounts for life cycle emissions over the entire food system. Overall, we identify that our estimate of PM$_{2.5}$ deaths from the global food system is underestimated given the limited accounting of contributions from sectors including agrochemical production, post-processing, consumption and inherent uncertainties in the causal pathways of emissions to exposure estimates as identified in section 4.3.

Our analysis has also identified key research gaps: (a) to date, the focus has been on agricultural production, with few studies examining sectors from other stages in the food system, and at national or sub-national scales. There is a dearth of studies examining the impacts of food demand and agricultural production activities in highly populated regions in Africa, South America and Asia, where countries also have a high share of GDP (15%–58% in Africa and Asia) attributed to agriculture (World Bank 2018b). Given that a 10% increase in global NH$_3$ emissions could result in 22 000 additional excess deaths (Lee et al 2013), it is important to focus on these regions that are also expected to see increases in NH$_3$ emissions in the future. (b) It is important to identify the regional-scale efficacy of NH$_3$ emissions controls in regulating ambient PM$_{2.5}$ (Pinder et al 2007). Notably, Bauer et al (2016) demonstrated that emissions from increased food production could be managed without deteriorating future air quality, assuming emission controls on combustion sources of NO$_x$. Given the substantial uncertainties in the emission inventories from agriculture (Crippa et al 2019) (see section 4.3.1), the extent of the impacts of NH$_3$, NO$_x$ and NMVOC emissions on ambient PM$_{2.5}$ at regional scales needs further investigation.
Table 4. Estimate of PM$_{2.5}$-attributable premature deaths from the global food system as developed in this review. Estimates are derived by using the median estimates reported by the listed studies and applying an allocation factor that identifies food versus non-food contributions from the emissions sector. These findings are largely underestimated given the paucity of emissions from the post-production and consumption stages, reported global underestimates in the magnitude of NH$_3$ emissions, the lack of sector-scale analysis of PM$_{2.5}$-attributable deaths in several regions including South America and Africa, and different methods and uncertainty in IER functions.

| Stage         | Sector                  | Region           | Study                                      | IER functions                                      | Non-adjusted PM$_{2.5}$-deaths | Allocation for the food v/s non-food contributions | Adjusted PM$_{2.5}$-deaths from the global food system |
|---------------|-------------------------|------------------|--------------------------------------------|----------------------------------------------------|--------------------------------|-------------------------------------------------|----------------------------------------------------------|
| Pre-production| Land-use                | Global           | Johnston et al (2012)                      | American Cancer Society study by Pope et al (1995) | 330 000                         | 1. Reduce contributions from waste burning (Kodros et al 2016) 2. Reduce contributions from wildfires (23%) and non-agriculture commodity driven land-use change (30%) (World Resources Institute 2014) | 70 000                                                   |
| Production    | Fertilizer production   | N/A              | Pozzer et al (2017)                        | Burnett et al (2014) as reported in GBD 2010       | 800 000                         | 93% global crop area diverted for food production (FAO 2020) | 750 000                                                   |
|               | On-farm energy use      | Europe, Asia, N/A|                                            |                                                    |                                |                                                 |                                                         |
|               | Livestock rearing       | North America    |                                            |                                                    |                                |                                                 |                                                         |
|               | Fertilizer use          |                  |                                            |                                                    |                                |                                                 |                                                         |
|               | Agricultural waste burning |                |                                            |                                                    |                                |                                                 |                                                         |
|               | Other emissions         |                  |                                            |                                                    |                                |                                                 |                                                         |
| Post-production| Food industry           | N/A              |                                            |                                                    |                                |                                                 |                                                         |
|               | Transportation          |                  |                                            |                                                    |                                |                                                 |                                                         |
|               | Retail and distribution |                  |                                            |                                                    |                                |                                                 |                                                         |
| Consumption   | Commercial cooking      | N/A              |                                            |                                                    |                                |                                                 |                                                         |
|               | Residential cooking     |                  |                                            |                                                    |                                |                                                 |                                                         |
| Waste         | Open burning            | Global           | Kodros et al (2016)                        | Burnett et al (2014) as reported in GBD 2010       | 190 000                         | 40% domestic waste composed of food (World Bank Group 2018) | 76 000                                                   |
|               | Controlled disposal     | N/A              |                                            |                                                    |                                |                                                 |                                                         |
|               |                         |                  |                                            |                                                    |                                |                                                 |                                                         |

Median PM$_{2.5}$ attributable deaths from the global food system: 890 000
4.2.3. Household cooking impacts on ambient PM$_{2.5}$ pollution burden

In this review, we thus far focus on ambient PM$_{2.5}$. However, it is worthwhile briefly discussing the expansive literature that examines household cooking impacts on both ambient and indoor PM$_{2.5}$ exposure. The use of solid fuels, such as coal, wood, crop residues and animal dung can elevate household PM$_{2.5}$ concentrations by 110–850 µg m$^{-3}$ higher in comparison to the use of gas or electricity (Shupler et al. 2018). As a result, 2.8 million premature deaths in 2015 have been linked to exposure to household PM$_{2.5}$ (Kodros et al. 2018), as well as non-fatal cardiovascular and respiratory conditions (Hystad et al. 2019). Recent studies have estimated that 12% of global population-weighted average ambient PM$_{2.5}$ exposure is attributed to household solid cooking fuels (Smith et al. 2014), with regional contributions ~10% in East Asia including China, and higher contributions in India (26%) and sub-Saharan Africa (37%) (Chafe et al. 2014, Smith et al. 2014). While there are challenges in separating the indoor versus outdoor contributions of emissions to PM$_{2.5}$, household cooking has been attributed to 450 000 excess deaths annually (Chafe et al. 2014). In China alone, household energy use for cooking was attributed to 182 000–260 000 excess deaths (Archer-Nicholls et al. 2016, Zhao et al. 2018). In India, residential energy use was linked to 34% ambient PM$_{2.5}$ exposure (Rooney et al. 2019) and contributed to 512 000 excess deaths (Conibear et al. 2018). However, contributions from cooking were not delineated. Given that emissions from residential energy use for heating and cooking dominate the contribution to PM$_{2.5}$ exposure in India, China and sub-Saharan Africa (Butt et al. 2016), we recommend that further research be directed to understanding the mitigation potential of cleaner fuels and technologies, especially at spatially explicit scales in these regions (Kuhn et al. 2016).

4.3. Sources of uncertainties

4.3.1. Characterization of NH$_3$ emissions and linkages to PM$_{2.5}$ formation

Estimates of PM$_{2.5}$-attributed deaths can vary around ±1 million globally due to uncertainties in emissions inventories alone (Crippa et al. 2019). Reducing uncertainties in NH$_3$ emissions inventories is critical for more accurate estimates of ambient PM$_{2.5}$ exposure. While NH$_3$ emissions from EDGAR are within a factor of three in comparison to satellite-derived emissions fluxes, at least 67% of the sources were underestimated by one order of magnitude or more (van Damme et al. 2018). Studies report large underestimates in total NH$_3$ emissions over agricultural areas that are as high as 40% in China (Zhang et al. 2017b, 2017c) and 200%–450% across the United States (Heald et al. 2012, Battye et al. 2016, Bray et al. 2017). These underestimates result from limited representations of the total magnitude and spatial and temporal distribution of NH$_3$ emissions from manure management and fertilizer use (Appel et al. 2011, Paulot et al. 2014, Hendriks et al. 2016, Balasubramanian et al. 2020, Ge et al. 2020), and are subsequently linked to large biases in the predictions of ambient PM$_{2.5}$ concentrations especially for PM-NO$_3$ formation (Punger and West 2013, Paolella et al. 2018).

A wide range of approaches have been adopted to reduce uncertainties in NH$_3$ emission inventories, including the use of inverse models that use observation data to constrain seasonality in NH$_3$ emissions (Paulot et al. 2014, Zhu et al. 2015), process models that capture interactions between crop, soil and weather to predict NH$_3$ emissions at site and regional scales (Cooter et al. 2012, Balasubramanian et al. 2017, Xu et al. 2019), and meta-analysis of field measurements (Pan et al. 2016). In addition, continued advances in capturing emissions from sources, such as small fires, domestic burning and peatland fires through products like GFED4, further research delineating emissions contributions from agriculture-driven land-use change, and estimating emissions from food waste will help improve our understanding of the PM$_{2.5}$ pollution burden from the food system.

4.3.2. Resolving uncertainties in AQMs and choice of model parametrization

Uncertainties in air quality modeling that result from model formulation and model parametrization can introduce uncertainties in estimates of PM$_{2.5}$ premature mortality. However, these concerns are not specific to the analysis of the global food system. It is infeasible to examine the entire extent of formulations and parametrizations to quantity embedded uncertainties (Solazzo et al. 2017). However, marginal PM$_{2.5}$ responses to additional emissions have smaller biases than PM$_{2.5}$ predictions in response to the absolute magnitude of emissions (Hogrefe et al. 2008). An important aspect of CTMs (Chemical Transport Models) is the choice of spatial resolution (Reddington et al. 2014). Kushta et al. (2018) found that premature mortality estimates varied by less than 3% when using a coarser CTM resolution (>100 km) in comparison to a finer population-scale spatial resolution (<20 km). Similarly, a fine spatial scale analysis (4–36 km grid dimensions) over the United States constrained PM$_{2.5}$-attributable mortality to ±10% (Thompson et al. 2014). In contrast, Punger and West (2013) found higher differences (∼30%) when scaling PM$_{2.5}$ exposure from a coarser scale of global models (>250 km) to 12 km × 12 km, with similar differences reported (27%) when switching from coarsest (∼69 km) to finest (∼5.9 km) grids for the United States using an RCM (Paolella et al. 2018). Despite similar methodologies, (Kodros et al. 2016) estimates of total annual, global PM$_{2.5}$-deaths were 13% lower in comparison to (Lelieveld
et al 2015) as a result of coarse AQM configuration. Thus, rigorous PM$_{2.5}$ evaluation on a case-by-case basis is recommended in comparison to standard model performance benchmarks (Emery et al 2017) before further evaluation for health assessment. Further model improvements should also focus on reducing uncertainties in capturing PM$_{2.5}$ formation that is non-linear in response to NH$_3$ emissions, as well as representations of secondary organic aerosol formation (Fuzzi et al 2015).

4.3.3. Exploring IER functions to link PM$_{2.5}$ exposure to PM$_{2.5}$-attributable deaths

Many studies use log-linear IER functions, wherein a given reduction in PM$_{2.5}$ concentrations would yield the same gains in health benefits (Marshall et al 2015). Supralinear IER functions, however, better represent premature mortality outcomes as a function of PM$_{2.5}$ exposure (Goodkind et al 2014), thereby resulting in greater benefits at lower PM$_{2.5}$ concentrations (Marshall et al 2015). The IER responses at relatively high levels of PM$_{2.5}$ represent a source of uncertainty as they are derived based on studies for North America and Europe where the annual average PM$_{2.5}$ exposure is less than 30 µg m$^{-3}$ and have different baseline health conditions compared to several parts of the world. Recent studies now account for impacts from regions with high PM$_{2.5}$ exposure, such as in China (Shiraiwa et al 2017, Yin et al 2017). Burnett et al (2018) estimated that global PM$_{2.5}$ excess deaths could be as high as 8.9 million if the IER functions were derived using cohort studies covering the entire range of global PM$_{2.5}$ exposure. Goodkind et al (2019) estimated that varying the IER functions resulted in a 21% difference in mortality estimates for the United States. In addition, PM$_{2.5}$-attributable damage should consider both chronic and sporadic exposure for episodic emissions sectors, such as fires (Johnston et al 2012), and account for toxicity resulting from PM$_{2.5}$ components (Shaffer et al 2019). Lelieveld et al (2015) identified that when carbonaceous PM$_{2.5}$ was assumed to be more toxic than inorganic PM$_{2.5}$, the resulting mortality attributed to agricultural emissions reduced from 20% to 7%. However, similar analysis for fires from land-use change and waste combustion could result in large estimates of PM$_{2.5}$-attributable deaths. The responses of human health to PM$_{2.5}$ toxicity, especially to components that are carcinogens or allergens, and the synergistic interactions resulting from organic fractions remain active areas of research (West et al 2016, Shiraiwa et al 2017, Landrigan et al 2018, Bates et al 2019).

5. Opportunities for PM$_{2.5}$ mitigation and policy implications

If the current shifts in diets, affluence and population growth trends continue, agricultural production will need to increase by 60%–100% by 2050 to meet future food demand (Tilman et al 2011, Tilman and Clark 2014, FAO 2018). This demand is expected to increase the environmental burden through increases in GHG emissions by 87%, cropland demand by 67%, water withdrawals by 65% and nitrogen fertilizer inputs by 860% (Springmann et al 2018a), but the potential increase in PM$_{2.5}$-health damage is less well understood. Likewise, few studies have evaluated the emissions reduction potential of farm-scale interventions (Kupper et al 2015, Xu et al 2017, Guthrie et al 2018), and the impact of reductions of emissions from agricultural production on ambient PM$_{2.5}$ (Bauer et al 2016, Pozzer et al 2017) and PM$_{2.5}$-attributable premature deaths (Giannadaki et al 2018, Crippa et al 2019). In addition, there is concern with regard to the inequity in air pollution exposure impacts that occur from demographic differences in emissions attributed to the consumption of goods and spatially distant impacts of emissions on PM$_{2.5}$ exposure (Tessum et al 2019). These environmental justice implications are of particular interest in the global food system, dependent on where and how food is cultivated, and further exacerbated by socioeconomic differences in access to adequate and nutrient-rich foods. Reducing these environmental and health impacts will require a ‘third Green Revolution’ that focuses on the adoption of sustainable diets, improved agricultural practices and the implementation of regulatory instruments (FAO 2018). Here, we briefly identify instruments that have been proposed for the global food system to meet climate targets (Bryngelsson et al 2016, Wollenberg et al 2016, Niles et al 2018) that have potential co-benefits in minimizing ambient PM$_{2.5}$ health burden, both within and beyond the farm gate (Kanter et al 2020).

5.1. ‘Eating enough’ and ‘eating right’

Individual dietary demands play a key role in determining the impacts of the global food system (Kearney 2010). Since 1961, global food consumption has increased by 400 kcal d$^{-1}$, with the largest increases in South Asia (>50%) and Latin America (>30%) (FAO 2020a), and is projected to further increase by 25% by 2050 (FAO 2017). Despite improvements in food supply equity in the past century, a triple burden of malnutrition exists in the form of undernutrition (690 million), obesity (1.9 billion adults and 42 million children) and micronutrient deficiencies (2 billion) (WHO 2018, FAO 2020c). Agricultural production will need to increase to meet global food demand, while also accounting for shifts towards animal-based foods that are expected to increase by nearly 30% for meat and 20%–58% for eggs and dairy by 2050 (Clark et al 2018). These increases will likely be accompanied by increases in PM$_{2.5}$ and precursor emissions, especially in Asia and Africa, which face the largest increases in food demand (Godfray et al 2010).
The paradigm of ‘eating right’ and ‘eating enough’ could be the key to mitigating environmental damage, including air quality impacts. Consuming only the required calories that meet individual metabolic and nutritional demands could improve health and climate outcomes (Niles et al 2018). Producing crops only for human consumption (i.e. plant-based foods) can increase caloric availability by 70% (Cassidy et al 2013), thus meeting not just current, but future global food demand (Berners-Lee et al 2018). Plant-based foods have been identified to have lower environmental impacts per serving in comparison to animal-based foods, especially ruminant meats from cattle, sheep and goats that have larger contributions compared to pork, poultry, eggs and dairy (Clark et al 2018, Poore and Nemecek 2018, Willett et al 2019). Springsmann et al (2016) estimated that a complete shift to vegetarian diets and increasing vegetables, fruits, lentils and grain consumption by >50% would reduce GHG emissions (3–11 Gt yr\(^{-1}\)) by 2050. An examination of emissions factors for animal type-specific manure management suggests that similar trends could be expected for PM\(_{2.5}\) pollution burden. However, the extent of the impact of shifts in diets needs further investigation. Reducing dependencies on animal-based foods could maximize both health and environmental benefits (Clark and Tilman 2017, Godfray et al 2018). It is thus imperative to establish spatially explicit impacts of the global food system on PM\(_{2.5}\) health impacts, with a focus on NH\(_{3}\) emissions, as well as emissions resulting from land-use change.

5.2. Managing food waste

Globally, food waste tripled between 1960 and 2011 (FAO 2011, Porter et al 2016) and is a contributor to emissions of primary PM\(_{2.5}\), NMVOC and SO\(_{2}\) as a result of disposal practices. Reducing consumer food waste by 50%, either by individual choice or through supply chain interventions, could result in a 10% reduction in fertilizer and land use while improving food security through 1300 trillion kcal savings yr\(^{-1}\) by 2050 (Clark et al 2018). Developing policies and infrastructure to shift the open burning of waste to controlled disposal, possibly coupled with energy recovery, could provide benefits in reducing PM\(_{2.5}\) pollution (Coventry et al 2016). However, tradeoffs in the form of increases in NH\(_{3}\) emissions that result from organic waste decomposition should be carefully evaluated (Wang and Zeng 2018).

5.3. Farm-scale interventions

The demand for food is expected to increase substantially, along with subsequent emissions, especially in Asia (by 40%) and Africa (by 47%) by 2050. While the agricultural contributions to ambient PM\(_{2.5}\) in these regions are small (3%-9%), in comparison to residential (27%-45%) and power generation (17%-26%) (Crippa et al 2019), even a 50% reduction in agricultural production emissions could reduce up to 130 000 PM\(_{2.5}\)-attributable premature deaths (Pozzer et al 2017). It is thus imperative to balance the need for food security with resulting health impacts, to reduce the expected large externalities and economic losses, through improvements in agricultural productivity as well as farm-scale mitigation strategies.

An increase in crop yields and reductions in farm-scale inefficiencies that are prevalent in lower-income countries in Sub-Saharan Africa, Mexico, India and Southeast Asia could reduce nitrogen and energy inputs to meet future food demand (Mueller et al 2012). Of high priority is the reduction of yield gaps (Lobell et al 2009, van Ittersum et al 2013) that are prevalent in 43 countries where crop yields are less than a third of their potential (Clark et al 2018). Suggested strategies include improving access to agricultural inputs, such as fertilizers, seeds and pesticides, especially in sub-Saharan Africa (Pradhan et al 2015). However, tradeoffs in increased yields and economic gains must be carefully weighed against increases in GHG, NH\(_{3}\) and PM\(_{2.5}\) emissions, and other environmental concerns. The impacts of alternative agricultural practices on air quality should be further evaluated, by exploring crop diversification through leguminous crops, intercropping and crop rotation (Garrity et al 2010, Ponismo et al 2015, Hunt et al 2019, 2020), organic cultivation (De Ponti et al 2012), the use of companion crops and exploiting the agronomic potential of natural NMVOC (Brilli et al 2019), and integrated pest management practices (Khan et al 2014, Hunt et al 2017).

Global NH\(_{3}\) emissions are expected to increase as a result of livestock production by 2050 (Bouwman et al 2013). Reducing NH\(_{3}\) emissions in current food systems will not only benefit air quality, but reduce economic losses for farmers that result from nitrogen volatilization (Good and Beatty 2011). Guthrie et al (2018) compiled a comprehensive list of mitigation interventions for Europe that include improvements in livestock management by modifying animal feed (NH\(_{3}\) reductions of 30%-45%) and increasing grazing time (<50%), structural interventions, such as redesigning animal housing and manure storage (>80%), adding control technologies, such as wet scrubbers (25%-65%), and modifying crop cultivation practices, including changes in nitrogen fertilizer type from urea to other forms of nitrogen, the use of fertilizer inhibitors and changing fertilizer application timing, loading rate and application mode (20%-70%). Similar assessments for emissions reduction potential and costs have also been reported by other studies in Europe (Kilmont and Winiwarter 2015) and the United States (Pinder et al 2007). The current suite of engineering solutions and best management practices could result in a 30% reduction in livestock-NH\(_{3}\) emissions and 20% in fertilizer-NH\(_{3}\) emissions (total 0.7 Tg yr\(^{-1}\)) for the United...
States alone (US EPA 2011). However, further region-specific studies are required.

5.4. Technological interventions
Technological solutions can reduce PM$_{2.5}$ pollution and have climate co-benefits within and beyond the post-production stage. Proposed interventions include improvements in energy efficiency by 20%–50% in food processing, distribution and retail, through correct specification and equipment use, cold chain-based food supplies, modal shifts in food transportation (Wakeland et al. 2012, Pelletier 2015, Niles et al. 2018, and new packaging technologies (Heller et al. 2019). Reducing household and ambient PM$_{2.5}$ exposure in regions that are reliant on solid fuel use for cooking have been identified as an important area of research. Ongoing efforts have focused on reducing disparity through the widespread adoption of cleaner fuels and cleaner technologies by the World Health Organization (WHO 2016) and by governments in India, China and across Africa (Aung et al. 2016, Anenberg et al. 2017). Recommended guidelines include switching from dirty household fuels including kerosene and coal to cleaner fuels higher on the energy ladder, such as LPG, ethanol, biogas and electricity, and introducing cheaper and cleaner cookstoves as promoted by the Global Alliance for Clean Cookstoves (Lewis and Pattanayak 2012, Anenberg et al. 2013, Pachauri et al. 2013) to reduce emissions of primary PM$_{2.5}$, NO$_x$ and SO$_2$, and the resulting health burden.

5.5. Regulatory instruments
Two regulatory instruments are of interest to minimize the impacts of food system emissions on PM$_{2.5}$ deaths. First, unlike economic sectors such as electricity generation and transportation, not all emissions sources within agriculture have been considered for emissions regulation in most parts of the world. While agriculture is not explicitly excluded from regulations in the United States, emissions regulation on primary PM$_{2.5}$ or secondary PM$_{2.5}$ precursors from farms is required only in non-attainment areas (US EPA 2017). For example, state regulations are imposed in California on crop growers, poultry, dairy and cattle farms, and agri-businesses (CARB 2019). However, on-farm emissions typically do not exceed the specified threshold and are thus exempt from most regulatory programs in the United States (US EPA 2017). Second, in the United States, the Clean Air Act regulations consider six criteria, air pollutants including NO$_x$, SO$_2$ and primary PM$_{2.5}$; NH$_3$ is currently not regulated. Given the large body of evidence identifying the key role NH$_3$ plays in regulating atmospheric chemistry, the US EPA Science Advisory Board has recommended regulatory approaches to treat NH$_3$ as a harmful PM$_{2.5}$ precursor (US EPA 2011). Such a regulatory approach should be considered worldwide.

Programs to study nitrogen management strategies and impacts on the environment and agricultural productivity have been adopted in Europe. The Convention on Long-Range Transboundary Air Pollution and the Gothenburg Protocol that have set targets to reduce SO$_2$, NO$_x$, NMVOC and NH$_3$ by 63%, 41%, 40% and 17%, respectively, by 2010 compared to 1990 to reduce acidification and surface water eutrophication, as well as preventing 48 000 excess deaths from PM$_{2.5}$ and ozone exposure (UNECE 2017). NH$_3$ emissions have already been reduced by 24% between 1990 and 2008, facilitated through multiple programs ranging from the adoption of alternative fertilizer types in Germany to providing financial incentives for improved nitrogen use in the Netherlands (EEA 2015). The United Kingdom also recently announced a plan to reduce NH$_3$ emissions by 15% by 2030 (Plautz 2018), demonstrating increased attention to cost-effective PM$_{2.5}$ abatement through the regulation of NH$_3$. A multifaceted regulation policy should be considered at the national scale to optimize the economic and environmental costs of farm-scale practices and alternative approaches.

5.6. Legislation, environmental and health protections
Legislation and environmental protections are important drivers of reducing the demands of agriculture on land-use change (Nolte et al. 2017, Seymour and Harris 2019). However, these strategies rarely account for the nature of agricultural commodities and consumption patterns (Henders et al. 2018). Deforestation rates decreased between 2004 and 2014 in Brazil following the establishment of conservation zones (Anderson et al. 2016). However, recent increases since 2017 (Amigo 2020) are a result of non-compliance with conservation agreements to meet the increased demand for soy, cattle and timber (Carvalho et al. 2019) and the impact of export-driven trade demands (Tester 2020). In Indonesia, national moratoriums as well as pledges from corporations to increase sustainable products in their supply chains have helped reduce conversions of primary forests and peatland for industrial palm production (Carlson et al. 2018, Gaveau et al. 2019). However, the impacts of such policies on air pollution and health exposure are relatively unexplored and limited to a few studies (Marlier et al. 2015, 2019).

In addition, health protection policies to promote healthier diets through dietary guidelines and legislation could offer co-benefits to both health and the environment (Clark et al. 2018). The implications of these policies on GHG emissions have been the subject of recent inquiry, with examples
Table 5. Key findings from the system-scale analysis of excess deaths occurring from exposure to PM$_{2.5}$ from the global food system.

| Findings | Implications |
|----------|--------------|
| The global food system is a significant contributor to total anthropogenic emissions of primary PM$_{2.5}$ (58%), NH$_3$ (72%), NO$_x$ (13%), SO$_2$ (9%), and NMVOC (19%). | 1. Important sources include land-use change, livestock and crop production, and agricultural waste burning. |
| Emissions from the global food system are linked to at least 890 000 annual PM$_{2.5}$-attributable deaths, which is equivalent to 23% of PM$_{2.5}$-deaths reported in the Global Burden of Disease Study 2015. | 2. Sectoral emission contributions vary by region. Agricultural production emissions dominate contributions in North America and Europe, while land-use change, manure management and agricultural waste burning emissions dominate contributions in Asia, Africa and South America. |
| There are uncertainties in establishing the impact of emissions from the global food system on PM$_{2.5}$-attributable deaths. | 1. 84% of estimated PM$_{2.5}$-attributable deaths from the global food system are a result of agricultural production. |
| There are likely many cost-effective opportunities to mitigate PM$_{2.5}$ pollution by reducing emissions from the global food system. | 2. Estimates of excess deaths are likely underestimated given the paucity in emissions data from the post-production and consumption stages, underestimated global NH$_3$ emissions, and lack of sector-scale analysis of PM$_{2.5}$-attributable deaths in South America and Africa. |

including the evaluation of national dietary recommendations (Behrens et al 2017), national-scale strategies to reduce dependencies on animal-based foods (Springmann et al 2018b), and expanding sustainability metrics to also account for macro and micronutrient delivery from food production (DeFries et al 2015, de Ruijer et al 2018). In addition, managing food pricing has been recommended as a tool to reduce GHG emissions, namely through GHG taxes (Springmann et al 2017), taxes on less healthy foods, such as refined sugar (Briggs et al 2016), and through subsidies and tax revenues (Hadjikakou 2017) albeit with concerns about disproportionate effects on those of lower socioeconomic status. PM$_{2.5}$-related pollutant emissions could also be achieved through programs that target reductions in waste (Porter et al 2016), food portioning (Story et al 2008) and food labeling akin to calorie labeling (Upham et al 2011, Leach et al 2016). Expanding environmental impact assessment to include impacts on PM$_{2.5}$ pollution burden deserves further study, given the downstream impacts of such policies on shifts in diet, food production, processing and waste disposal. Finally, it is essential to consider the environmental justice implications of food and agricultural systems for the world at large.

6. Highlights and research needs

The recent growth in understanding the global food system and its complex interplay with energy, material, water and land use has expanded our understanding of the large burden it places on the environment (Springmann et al 2018a). Indeed, a comprehensive accounting of food sustainability requires further consideration of major diets and food...
commodities, the processes that drive the food system and expanding the suite of environmental impacts (Halpern et al 2019). Our review adds to the conversation about global food system sustainability by identifying the large health burden resulting from exposure to ambient PM$_{2.5}$. Here, we show that PM$_{2.5}$-related emissions from the global food system are linked to 890 000 PM$_{2.5}$-attributable premature deaths annually, which is equivalent to 23% of the 3.9 million ambient PM$_{2.5}$-attributable deaths reported in the Global Burden of Disease Study 2015. These findings are, however, underestimated, given the paucity of emissions from food post-production and consumption stages, the overall global underestimate in emissions of NH$_3$ and the lack of PM$_{2.5}$ exposure impact studies for several emissions sectors and in regions including South America and Africa. A summary of our key findings is listed in table 5.

Additional empirical research is needed to reduce uncertainties in the characterization of emissions across multiple spatial and temporal scales to support air quality forecasting, and with a focus on expected future trends in production, consumption and food losses in low- and middle-income countries. Research opportunities abound in identifying improvements in energy and resource use in the food industry, retail and distribution, and transportation. Furthermore, systematic and region-scale efforts, especially in Asia, Africa and South America, are required to establish how the identified emissions mitigation strategies could deliver cost-effective reductions in ambient PM$_{2.5}$ concentrations and PM$_{2.5}$-attributable premature deaths. With diets shifting towards animal-based and more processed foods, and increases in global caloric consumption, additional environmental and health burdens resulting from degrading air quality are expected. However, by considering variability in regional shifts in future food demand and production, strategies that encompass a wide range of regulatory, technological and educational tools that encourage health and environmentally conscious diets can be implemented to sustainably manage these increases with minimal impacts on air pollution. Given the recent interest in food system research in the context of climate and other environmental impacts, we argue that the se studies should further account for damage from PM$_{2.5}$ pollution as a key indicator of both human and environmental health.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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References

Abdullahi K L, Delgado-Saborit J M and Harrison R M 2013 Emissions and indoor concentrations of particulate matter and its specific chemical components from cooking: a review Atmos. Environ. 71 260–94
Akagi S K, Yokelson R J, Wiedinmyer C, Alvarado M J, Reid J S, Karl T, Crounse J D and Wennberg P O 2011 Emission factors for open and domestic biomass burning for use in atmospheric models Atmos. Chem. Phys. 11 4039–72
Amigo I 2020 The Amazon's fragile future Nature 578 505–7
Anderson L O, Martino S, Harding T, Kuralbayeva K and Lima A 2016 The effects of land use regulation on deforestation:
evidence from the Brazilian Amazon # 172, OccRP Working Papers (Oxford Centre for the Analysis of Resource Rich Economies, University of Oxford)

Andreae M O and Merlet P 2001 Emission of trace gases and aerosols from biomass burning Glob. Biogeochem. Cycle. 15 955–66

Aneja V P, Schlesinger W H and Aneja S P 2015 Effects of intensively managed agriculture on the atmospheric environment EM Air Waste Manage. Assoc. Mag. Environ. Manage. 65 24–30

Aneja V P, Schlesinger W H and Erisman J W 2009 Effects of agriculture upon the air quality and climate: research, policy, and regulations Environ. Sci. Technol. 43 4234–40

Anenberg S C, Balakrishnan K, Jetter J, Masera O, Moss J and Ramanathan V 2013 Cleaner cooking solutions to achieve health, climate, and economic benefits Environ. Sci. Technol. 47 3944–52

Anenberg S C, Henze D K, Lacey F, Irfan A, Kinney P, Kleinman G and Pillaristetti A 2017 Air pollution-related health and climate benefits of clean cookstove programs in Mozambique Environ. Res. Lett. 12 025006

Appel K W, Foley K M, Bash J O, Pinder R W, Dennis R L, Allen D J and Pickering K 2011 A multi-resolution assessment of the Community Multiscale Air Quality (CMAQ) model v4.7 wet deposition estimates for 2002–2006 Geosci. Model Dev. 4 317–71

Apte J S, Brauer M, Cohen A J, Ezzati M and Pope C A 2018 Ambient PM 2.5 reduces global and regional life expectancy Environ. Sci. Technol. 52 546–51

Archer–Nicholls S et al 2016 The regional impacts of cooking and heating emissions on ambient air quality and disease burden in China Environ. Sci. Technol. 50 9416–23

Arora P and Jain S 2016 A review of chronological development in cookstove assessment methodic challenges and way forward Renew. Sustain. Energy Rev. 55 203–20

Aung T W, Jain G, Sethuraman K, Baumgartner J, Reynolds C, Grieshop A P, Marshall J D and Brauer M 2016 Health and climate–relevant pollutant concentrations from a carbon–finance approved cookstove intervention in rural India Environ. Sci. Technol. 50 7228–38

Bachmann J D et al 2007 Will the circle be unbroken: a history of the U.S. National Ambient Air Quality Standards J. Air Waste Manage. Assoc. 57 652–97

Balasubramanian S, Koloutsou–Vakakis S, McFarland D M and Rood M J 2015 Reconsidering emissions of ammonia from chemical fertilizer usage in Midwest USA J. Geophys. Res. Atmos. 120 6232–46

Balasubramanian S, McFarland D M, Koloutsou–Vakakis S, Fu K, Menon R, Lehmann C M B and Rood M J 2020 Effect of grid resolution and spatial representation of NH3 emissions from fertilizer application on predictions of NH3 and PM2.5 concentrations in the United States Con Belt Environ. Res. Commun. 2 025001

Balasubramanian S, Nelson A, Koloutsou–Vakakis S, Lin J, Rood M J, Myles L and Bernacchi C 2017 Evaluation of DeNitrification DeComposition model for estimating ammonia fluxes from chemical fertilizer application Agric. For. Meteorol. 237–238 123–34

Bates J T et al 2019 Review of acellular assays of ambient aerosol particulate matter oxidative potential: methods and relationships with composition, sources, and health effects Environ. Sci. Technol. 53 4003–19

Battey R, Battey W, Overcash C and Fudge S 1994 Development and selection of ammonia emission factors Final report, February–August 1994 (No. PB–95–123915/XAB) EC/R, Inc. Durham, NC (United States) (https://doi.org/10.1103/PhysRevLett.75.2954)

Battey W H, Bray C D, Aneja V P, Tong D, Lee P and Tang Y 2016 Evaluating ammonia (NH3) predictions in the NOAA National Air Quality Forecast Capability (NAQFC) using in situ aircraft, ground-level, and satellite measurements from the DISCOVER-AQ Colorado campaign Atmos. Environ. 140 342–51

Bauer S E, Im U, Mezuman K and Gao C Y 2019 Desert dust, industrialization, and agricultural fires: health impacts of outdoor air pollution in Africa J. Geophys. Res. Atmos. 124 4104–20

Bauer S E, Tsigaridis K and Miller R 2016 Significant atmospheric aerosol pollution caused by world food cultivation Geophys. Res. Lett. 43 5949–400

Behera S N, Sharma M, Aneja V P and Balasubramanian R 2013 Ammonia in the atmosphere: a review on emission sources, atmospheric chemistry and deposition on terrestrial bodies Environ. Sci. Pollut. Res. 20 8092–131

Behrens P, Kieffe–de Jong J C, Bosker T, Rodriguez J F D, de Koning A and Tukker A 2017 Evaluating the environmental impacts of dietary recommendations Proc. Natl Acad. Sci. USA 114 13412–7

Berners–Lee M, Kennedy C, Watson R and Hewitt C N 2018 Current global food production is sufficient to meet human nutritional needs in 2050 provided there is radical societal adaptation Elementa 6 1–52

Beusen A H W, Bouwman A F, Heuberger P S C, van Drengt G and van der Hoek K W 2008 Bottom–up uncertainty estimates of global ammonia emissions from global agricultural production systems Atmos. Environ. 42 6067–77

Bond T C et al 2013 Bounding the role of black carbon in the climate system: a scientific assessment J. Geophys. Res. Atmos. 118 10789–10822

Bouwman L, Goldewijk K K, van der Hoek W, Beusen A H W, van Vuuren D P, Willems R J, Rufino M C and Stehfest E 2013 Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period Proc. Natl Acad. Sci. USA 110 20882–7

Bray C D, Battey W, Aneja V P, Tong D, Lee P, Tang Y and Nowak J B 2017 Evaluating ammonia (NH3) predictions in the NOAA National Air Quality Forecast Capability (NAQFC) using in-situ aircraft and satellite measurements from the CalNex2010 campaign Atmos. Environ. 163 65–76

Briggs A D M, Kuhlbacher A, Tiffen R and Scarborough P 2016 Simulating the impact on health of internalising the cost of carbon in food prices combined with a tax on sugar-sweetened beverages BMC Public Health 16 1–14

Brilli F, Loreto F and Baccelli I 2019 Exploiting plant volatile organic compounds (VOCs) in agriculture to improve sustainable defense strategies and productivity of crops Front. Plant Sci. 10 1–8

Brilli L et al 2017 Review and analysis of strengths and weaknesses of agro-ecosystem models for simulating C and N fluxes Sci. Total Environ. 598 445–70

Brodt S, Kramer K J, Kendall A and Feenstra G 2013 Comparing environmental impacts of regional and national-scale food supply chains: a case study of processed tomatoes Food Policy 42 106–14

Brown E and Elliott R N 2005 On-farm energy use characterizations American Council for an Energy–Efficient Economy

Brunori G et al 2016 Are local food chains more sustainable than global food chains? Considerations for assessment Sustainability 8 449

Bryngelson D, Wiersenius S, Hedenus F and Sonesson U 2016 How can the EU climate targets be met? A combined analysis of technological and demand-side changes in food and agriculture Food Policy 59 152–64

Burgardt R T et al 2014 An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure Environ. Health Perspect. 122 397–403

Burgardt R T et al 2018 Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter Proc. Natl Acad. Sci. 115 201803222

Butt E W et al 2016 The impact of residential combustion emissions on atmospheric aerosol, human health, and climate Atmos. Chem. Phys. 16 873–905
CARR 2019 Senate Bill No. 700—Chapter number 479 (available at: https://www.arb.ca.gov/ag/sb700/sb700.htm) (Accessed July 2020)

Carlson K M, Heilmayr R, Gibbons H K, Noojipady P, Burns D N, Morton D C, Walker N F, Paoli G D and Kremen C 2018 Effect of oil palm sustainability certification on deforestation and fire in Indonesia Proc. Natl. Acad. Sci. USA 115 121–6

Carter S, Herold M, Arahata V, de Bruin S, de Sy V, Kooistra L and Rufino M C 2018 Agriculture-driven deforestation in the tropics from 1990–2015: emissions, trends and uncertainties Environ. Res. Lett. 13 014002

Carvalho W D, Mustin K, Hilário R R, Vasconcelos I M, Eilkes V and Fearnside P M 2019 Deforestation control in the Brazilian Amazon: a conservation struggle being lost as agreements and regulations are subverted and bypassed Perspect. Ecol. Conserv. 17 122–30

Cassidy E S, West P C, Gerber J S and Foley J A 2013 Redefining agricultural yields: from tonnes to people nourished per hectare Environ. Res. Lett. 8 034015

Chafe Z A, Brauer M, Klimont Z, van Dingenen R, Mehta S, Rao S, Riiali K, Dentener F and Smith K R 2014 Household cooking with solid fuels contributes to ambient PM2.5 air pollution and the burden of disease Environ. Health Perspect. 122 1314–20

Clark M, Hill J D and Tilman D 2018 The diet, health, and environment trilemma Annu. Rev. Environ. Resour. 43 109–34

Clark M and Tilman D 2017 Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice Environ. Res. Lett. 12 044016

Coffey E R, Muvandimwe D, Hagar Y, Wiedinmyer C, Clark M, Hill J D and Tilman D 2018 The diet, health, and environment trilemma Annu. Rev. Environ. Resour. 43 109–34

Coofer E J, Bush J O, Benson V and Ran L 2012 Linking agricultural crop management and air quality models for national to regional-scale nitrogen assessments Biogeochemistry 9 4023–35

Conibear L, Butt E W, Knote C, Arnold S R and Spracklen D V 2018 Residential energy use emissions dominate health impacts from exposure to ambient particulate matter in India Nat. Commun. 9 1–9

Cooter E J, Bush J O, Benson V and Ran L 2012 Linking agricultural crop management and air quality models for regional to national-scale nitrogen assessments Biogeochemistry 9 4023–35

Coventry Z A, Tize R and Karunanithi A T 2016 Comparative life

De Oliveira G, Chen J M, Mataelli G A V, Chaves M E D, Seixas H T, Da Cardozo F S, Shimabukuro Y E, He L, Stark S C and Dos Santos C A C 2020 Rapid recent deforestation incursion in a vulnerable indigenous land in the Brazilian Amazon and fire-driven emissions of fine particulate aerosol pollutants Forests 11 829

De Ponti T, Rijk B and van Iersel M K 2012 The crop yield gap between organic and conventional agriculture Agric. Syst. 108 1–9

De Ruiter H, Macciardi M J, Matthews R B and Smith P 2018 Moving beyond calories and protein: micronutrient assessment of UK diets and land use Glob. Environ. Change 52 106–17

DeFries R, Fanzo J, Remans R, Palm C, Wood S and Aederman T L 2015 Metrics for land–rare food production Agriculture Science 349 238–40

Deng J, Li C and Wang Y 2015 Modeling ammonia emissions from dairy production systems in the United States Atmos. Environ. 114 8–18

Dickinson K L et al 2015 Research on emissions, air quality, climate, and cooking technologies in Northern Ghana (REACTCTING): state rationale and protocol BMC Public Health 15 126

Domingo N G et al 2021 Air quality-related health damages of food Proceedings of the National Academy of Sciences 118 e2013637118

Edwards R, Princevach M, Weltman R, Ghasemian M, Arora N K and Bond T 2017 Modeling emission rates and exposures from outdoor cooking Atmos. Environ. 164 50–60

EAA 2013 Change in emissions of ammonia compared with the 2010 NECD and Gothenburg protocol targets (EEA member countries) National Emissions reported to the Convention on Long-range Transboundary Air Pollution (available at: www.eea.europa.eu/data-and-maps) (Accessed November 2020)

EAA 2016 EMEP/EEA air pollutant emission inventory guidebook 2016 EEA Rep. N2/21 (available at: www.eea.europa.eu/themes/air/air-pollutants-inventory-data/) (Accessed October 2020)

EIA 2016 Industrial sector energy consumption vol DOE/EIA-04 (U.S. Energy Information Administration) (available at: www.eia.gov/outlooks/seo/) (Accessed February 2020)

Ellis E C, Guldريق K K, Siebert S, Lightman D and Ramankutty N 2010 Anthropogenic transformation of the biomes, 1700–2000 Glob. Ecol. Biogeogr. 19 589–606

Emery C, Liu Z, Russell A G, Odman M T, Tarwood G and Kumar N 2017 Recommendations on statistics and benchmarks to assess photochemical model performance J. Air Waste Manage. Assoc. 67 582–98

Erisman J W, Bleeker A, Hensen A and Vermeulen A 2008a Agricultural air quality in Europe and the future perspectives Atmos. Environ. 42 3209–17

Erisman J W, Galloway J N, Seitzinger S, Bleeker A, Dic N B, Ronchi Petacca A M, Leach A M and de Vries W 2013 Consequences of human modification of the global nitrogen cycle Philos. Trans. R. Soc. B 368 20130116

Erisman J W, Sutton M A, Galloway J, Klimont Z and Winisower W 2008b How a century of ammonia synthesis changed the world Nat. Geosci. 1 636–9

Eurostat 2019 Freight Transport Statistics (available at: https://ec.europa.eu/transport/data/database) (Accessed February 2020)

FAO 2010 Global Food Losses and Food Waste: Extent, Causes and Prevention (available at: www.fao.org/3/mb060e/mb060e.pdf) (Accessed December 2019)

FAO 2018 The Future of Food and Agriculture—Alternative Pathways to 2050 (available at: www.fao.org/global-perspectives-studies/resources/detail/en/c/1157074/) (Accessed January 2020)

FAO 2020a Food and Agriculture Organization of the United Nations Statistical Database (FAOSTAT) (available at: www.fao.org/foodandfarming/fbs) (Accessed October 2020)

FAO 2020b New Food Balances FAOSTAT (available at: www.fao.org/foodandfarming/fbs) (Accessed September 2020)
Grizzetti B, Pretato U, Lasaletta L, Billen G and Garnier J 2013 The contribution of food waste to global and European nitrogen pollution Environ. Sci. Policy 33 186–95
Gu Y, Wong T W, Law C K, Dong G H, Ho K F, Yang Y and Yim S H L 2018 Impacts of sectoral emissions in China and the implications: air quality, public health, crop production, and economic costs Environ. Res. Lett. 13 084008
Guenthner A, Geron C, Pierce T, Lamb B, Harley P and Fall R 2000 Natural emissions of non-methane volatile organic compounds, carbon monoxide, and oxides of nitrogen from North America Atmos. Environ. 34 2205–30
Guo H, Kota S H, Chen K, Sahu S K, Hu J, Ying Q, Wang Y and Zhang H 2018 Source contributions and potential reductions to health effects of particulate matter in India Atmos. Chem. Phys. 18 15219–29
Guthrie S, Dunkerley T, Tabaqchali H, Harshfield A, Loppolo B and Manville C 2018 Impact of Ammonia Emissions from Agriculture on Biodiversity: An Evidence Synthesis (available at: https://royalsociety.org/~media/policy/projects/ evidence-synthesis/Ammonia/Ammonia-report.pdf) (Accessed December 2019)
Gysel N, Welch W A, Chen C L, Dixit P, Cocker D R, Karavalakis G, Cocker D R and Karavalakis G 2018 Particulate matter emissions and gaseous air toxic pollutants from commercial meat cooking operations J. Environ. Sci. 65 162–70
Hadjikakou M 2017 Trimming the excess: environmental impacts of discretionary food consumption in Australia Econ. Econ. 131 119–28
Halpern B S et al 2019 Putting all foods on the same table: achieving sustainable food systems requires full accounting Proc. Natl. Acad. Sci. USA 116 18152–6
Heal C L et al 2012 Atmospheric ammonia and particulate inorganic nitrogen over the United States Atmos. Chem. Phys. 12 10295–10312
Health Effects Institute 2019 Air-quality-related health damages of maize Environ. Sci. Technol. 53 15219–29
Heo H, Kota S H, Law C K, Sahu S K, Hu J, Ying Q, Wang Y and Zhang H 2018 Source contributions and potential reductions to health effects of particulate matter in India Atmos. Chem. Phys. 18 15219–29
Heller M C, Selke S E M and Keoleian G A 2019 Mapping the influence of food waste in food packaging environmental performance assessments J. Ind. Ecol. 23 480–95
Henders S, Ostwald M, Verendel V and Ibisch P 2018 Do national strategies under the UN biodiversity and climate conventions address agricultural commodity consumption as deforestation driver? Land Policy 70 580–90
Hendriks C, Kranenburg R, Kuenen J J P, van den Bril B, Verguts V, Hendriks C, Kranenburg R, Kuenen J J P, van den Bril B, Verguts V and da Vries W 2020 Modeling atmospheric ammonia using agricultural emissions with improved spatial variability and temporal dynamics Atmos. Chem. Phys. 20 1–51
Giannadaki D, Giannakis E, Pozzer A and Lelieveld J 2018 Estimating health and economic benefits of reductions in air pollution from agriculture Sci. Total Environ. 622–623 1304–16
Gilmore E A, Heo J, Muller N Z, Tessum C W, Hill J D, Marshall J D and Adams P J 2019 An inter-comparison of the social costs of air quality from reduced-complexity models Environ. Res. Lett. 14 074016
Giltrap D L, Saggar S, Rodrigues J and Bishop P 2017 Modelling NH3 volatilisation within a urine patch using NZ-DNDC Nutr. Cycl. Agroecosys. 108 266–77
Godfray H C J, Aveyard P, Garnett T, Hall J W, Key T J, Lorimer J, Moyo J G, Kalinganire A, Larwanou M and Bayala J 2010 Evergreen Agriculture: a robust approach to sustainable food security in Africa Food Secur. 2 197–214
Godfray H C J, Crute I R, Haddad L, Muir J F, Nisbett N, Lawrence D, Pretty J, Robinson S, Toulmin C and Whiteley R 2010 The future of the global food system Philos. Trans. R. Soc. B 365 2769–77
Goebies M D, Strader R and Davidson C 2003 An ammonia emission inventory for fertilizer application in the United States Atmos. Environ. 37 2593–2596
Goldemberg J, Martinez-Gomez J, Sagar A and Smith K R 2018 Householder air pollution, health, and climate change: cleaning the air Environ. Res. Lett. 13 030201
Good A G and Beatty P H 2011 Fertilizing nature: a tragedy of excess in the commons PLoS Biol. 9 1–9
Goodkind A L, Coggins J S and Marshall J D 2014 A spatial model of air pollution: the impact of the concentration-response function J. Assoc. Environ. Resour. Econ. 1 451–79
Goodkind A L, Tessum C W, Coggins J S, Hill J D and Marshall J D 2019 Fine-scale damage estimates of particulate matter air pollution reveal opportunities for location-specific mitigation of emissions Proc. Natl. Acad. Sci. 116 8775–80
Griesshop A P, Marshall J D and Kandlikar M 2011 Health and climate benefits of cookstove replacement options Energy Policy 39 7530–42
Foley J A et al 2005 Global consequences of land use science Science 309 570–4
Foley J A et al 2011 Solutions for a cultivated planet Nature 478 337–42
Fryar C D, Hughes J P, Herrick K A and Ahluwalia N 2018 Food Consumption Among Adults in the United States, 2013–2016 (available at: www.cdc.gov/nchs/data/databriefs/db322_table.pdf#1) (Accessed August 2020)
Fuchs R, Prestele R and Verburg P H 2018 A global assessment of gross and net land change dynamics for current conditions and future scenarios Earth Syst. Dyn. 9 441–58
Fuzzi S et al 2015 Particulate matter, air quality and climate: lessons learned and future needs Atmos. Chem. Phys. 15 6215–99
Garrity D P, Akinfenwi F K, Ajayi O C, Woldemassay S G, Mowo J G, Kalinganire A, Larwanou M and Bayala J 2010 Evergreen Agriculture: a robust approach to sustainable food security in Africa Food Secur. 2 197–214
Gaveau D L A, Locatelli B, Salim M A, Yen H, Pacheco P and Shell D 2019 Rise and fall of forest loss and industrial plantations in Borneo (2000–2017) Conserv. Lett. 12 1–8
Ge X, Schaap M, Kranenburg R, Segers A, Reinds G J, Kros H and de Vries W 2020 Modeling atmospheric ammonia using agricultural emissions with improved spatial variability and temporal dynamics Atmos. Chem. Phys. 20 1–51

IOP Publishing
Environ. Res. Lett. 16 (2021) 103004
S Balasubramanian et al
Hunt N D, Hill J D and Liebman M 2019 Cropping system diversity effects on nutrient discharge, soil erosion, and agronomic performance Environ. Sci. Technol. 53 1344–52
Hunt N D, Liebman M, Thakrar S K and Hill J D 2020 Fossil energy use, climate change impacts, and air-quality-related human health damages of conventional and diversified cropping systems in Iowa, USA Environ. Sci. Technol. 54 11082–14
Hystad P et al 2019 Health effects of household solid fuel use: findings from 11 countries within the prospective urban and rural epidemiology study Environ. Health Perspect. 8 057003
IHME GBD Results Tool—Particulate Matter Pollution GBD Results Tool (available at: https://gbd2017.healthdata.org/gbd-search/) (Accessed November 2020)
James S J and James C 2010 The food cold-chain and climate change Food Res. Int. 43 1944–56
Jethva H, Chand D, Torres O, Gupta P, Lyapustin A and Patadia F 2018 Agricultural burning and air quality over Northern India: a synergistic analysis using NASA’s A-train satellite data and ground measurements Aerosol. Air Qual. Res. 18 1756–71
Jiang R and Bell M I 2008 A comparison of particulate matter from biomass-burning rural and non-biomass-burning urban households in northeastern China Environ. Health Perspect. 116 907–14
Johnson M et al 2019 In-home emissions performance of cookstoves in Asia and Africa Atmosphere 10 1–17
Johnston F H, Henderson S B, Chen Y, Randerson J T, Marlier M, Johnson M A et al 2018 The Lancet Commission on pollution and health Lancet 391 462–512
Lang J, Tian J, Zhou Y, Li K, Chen D, Huang Q, Xing X, Zhang Y and Cheng S 2018 A high temporal-spatial resolution air pollutant emission inventory for agricultural machinery in China J. Clean. Prod. 183 1110–21
Langridge P J et al 2018 The contribution of outdoor air pollution sources to premature mortality on a global scale Nature 529 367–71
Lelieveld J, Klingmüller K, Pozzer A, Burnett R T, Haines A and Rudolph J 2015 Response of global particulate-matter-related mortality to changes in local precursor emissions Environ. Sci. Technol. 49 4335–44
Lelieveld J, Evans J S, Finas M, Giannadaki D and Pozzer A 2015 The contribution of outdoor air pollution sources to premature mortality on a global scale Nature 529 367–71
Leach A M et al 2016 Environmental impact food labels combining carbon, nitrogen, and water footprints Food Policy 61 213–23
Lee C J, Martin R V, Henze D K, Brauer M, Cohen A and Van Donkelaar A 2015 Response of global particulate-matter-related mortality to changes in local precursor emissions Environ. Sci. Technol. 49 4335–44
Kiely L et al 2019 Multi-pollutant emissions from the burning of major agricultural residues in China and the related health-economic effects Atmos. Chem. Phys. 21 8457–88
Li C et al 2017b Trends in chemical composition of global and regional population-weighted fine particulate matter estimated for 25 years Environ. Sci. Technol. 51 11185–95
Li X, Duan L, Wang S, Duan J, Guo X, Yi H, Hu J, Li C and Hao J 2007 Emission characteristics of particulate matter from rural household biofuel combustion in China Energy Fuel 21 8457–88
Lim T-T, Heber A J, Nj I-Q, Sutton A L and Shao P 2003 Odor and gas release from anaerobic treatment lagoons for swine manure J. Environ. Qual. 32 406–16
Lin Y, Zhang Y, Fan M and Bao M 2020 Heterogeneous formation of particulate nitrate under ammonium-rich regimes during the high-PM2.5 events in Nanjing, China Atmos. Chem. Phys. 20 3999–4011
Lipinski B, Hanson C, Lomax J, Kitinjoo L, Waite R and Searchinger T 2013 Creating a sustainable food future: reducing food loss and waste World Resour. Inst. 1–40 (available at: www.worldresourcesreport.org) (Accessed July 2020)

Liu L et al 2019 Health and climate impacts of future United States land freight modelled with global-to-urban models Nat. Sustain. 2 105–12

Lobell D B, Cassman K G and Field C B 2009 Crop yield gaps: their importance, magnitudes, and causes Annus. Rev. Environ. Resour. 34 179–204

Lu C and Tian H 2017 Global nitrogen and phosphorus fertilizer use for agriculture production in the past half century: shifted hot spots and nutrient imbalance Earth Syst. Sci. Data 9 181–92

Mallye C et al 2021 Integrated assessment of global climate, air pollution, and dietary, malnutrition and obesity health impacts of food production and consumption between 2014 and 2018 Environ. Res. Commun. (https://doi.org/10.1088/2515-7620/ac0a9)

Manuwe F, Lemma B and Woldeamanuel T 2018 Emissions and fuel use performance of two improved stoves and determinants of their adoption in Dodolla, Southeastern Ethiopia Sustain. Environ. Res. 28 52–38

Marlier M E et al 2019 Fires, smoke exposure, and public health: an integrative framework to maximize health benefits from peatland restoration GeoHealth 3 178–89

Marlier M E, Defries R S, Kim P S, Koplitz S N and Jacob D J 2015 Fire emissions and regional air quality impacts from fires in oil palm, timber, and logging concessions in Indonesia Environ. Res. Lett. 10 155005

Marshall J D, Apte J S, Coggins J S and Goodkind A L 2015 Blue skies blue? Environ. Sci. Technol. 49 13929–36

Martin D A 2019 Linking fire and the United Nations Sustainable Development Goals Sci. Total Environ. 662 547–58

McQuilling A M and Adams P J 2015 Semi-empirical process-based models for ammonia emissions from beef, swine, and poultry operations in the United States Atmos. Environ. 120 127–36

Megaritis A G, Fountoukis C, Charalampidis P E, Pilinis C and Pandis S N 2013 Response of fine particulate matter concentrations to changes of emissions and temperature in Europe Atmos. Chem. Phys. 13 3423–43

Menghewani V, Zerrifi H, Dwivedi P, Marshall J D, Griesshop A and Balilis R 2019 Determinants of cookstoves and fuel choice among rural households in India Ecosyst. Environ. 16 21–60

Merciai S and Schmidt J 2016 Physical/Hybrid supply and use tables. Methodological report EU FP7 DESIRE (available at: https://desireproject.eu/documents/category/3-public-deliverables%20%28%29) (Accessed June 2020)

Merciai S and Schmidt J 2018 Methodology for the construction of global multi-regional hybrid supply and use tables for the EIOXBASE v3 Database J. Ind. Ecol. 22 516–31

Miettinen J, Shi C and Liew S C 2016 Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 with changes since 1990 Glob. Ecol. Conserv. 8 62–78

Mueller N D, Gerber J S, Johnston M, Ray D K, Ramankutty N and Foley J A 2012 Closing yield gaps through nutrient and water management Nature 490 254–7

Muller N and Mendelsohn R 2010 Weighing the value of a ton of pollution Regulation 33 20–24

Nasir Z A and Colbeck I 2013 Particulate pollution in different housing types in a UK suburban location Sci. Total Environ. 445–446 165–76

Ndambi O A, Pelster D E, Owino J O, De Buuisong F and Vellinga T 2019 Manure management practices and policies in Sub-Saharan Africa: implications on manure quality as a fertilizer Front. Sustain. Food Syst. 3 1–14

Nelson A J et al 2017 Season-long ammonia flux measurements above fertilized corn in central Illinois, USA, using relaxed eddy accumulation Agric. For. Meteorol. 239 202–12

Ni H et al 2015 Emission characteristics of carbonaceous particles and trace gases from open burning of crop residues in China Atmos. Environ. 123 399–406

Ni Q J, Heber A J, Darr M J, Lim T T, Diehl C A and Bogan B W 2009 Air quality monitoring and on-site computer system for livestock and poultry environment studies Trans. ASABE 52 937–47

Niles M T et al 2018 Climate change mitigation beyond agriculture: a review of food system opportunities and implications Renew. Agric. Food Syst. 33 1–12

Nolte C, Gobbi B, Le Polain De Waroux Y, Piquer-Rodriguez M, Butsic V and Lambin E F 2017 Decentralized land use zoning reduces large-scale deforestation in a major agricultural frontier Ecol. Econ. 136 30–40

Odorico P D, Carr J A, Laio F, Ridolfi L and Vandoni S 2014 Feeding humanity through global food trade Earth’s Future 2 458–69

Oenema O, Velthof G, Amann M, Kliment Z and Winiszawer W 2012 Emissions from agriculture and their control potentials TSAP Report 3, version 2.1 International Institute for Applied Systems Analysis (IIASA), Laxenburg (https://doi.org/10.016/fstylesenviron.2012.03.028)

Pachauri S, Van Ruijven B J, Nagai Y, Riahi K, van Vuuren D P, Brew-Hammond A and Nakicenovic N 2013 Pathways to achieve universal household access to modern energy by 2030 Environ. Res. Lett. 8 024015

Pan B, Lam S K, Mosier A, Luo Y and Chen D 2016 Ammonia volatilization from synthetic fertilizers and its mitigation strategies: a global synthesis Agric. Ecosyst. Environ. 232 283–9

Pandey A, Patel S, Perez S, Tiwari S, Yadamia G, Chow J C, Watson J G, Biswas P and Chakraborty R K 2017 Aerosol emissions factors from traditional biomass cookstoves in India: insights from field measurements Atmos. Chem. Phys. 17 13721–9

Paolella D A, Tessum C W, Adams P J, Apte J S, Chambliss S, Hill J, Muller N Z and Marshall J D 2018 Effect of model spatial resolution on estimates of fine particulate matter exposure and exposure disparities in the United States Environ. Sci. Technol. Lett. 5 436–41

Parfitt J, Barthel M and MacNaughton S 2010 Food waste within food supply chains: quantification and potential for change to 2050 Philos. Trans. R. Soc. B 365 3065–81

Pattee E and Qiu G 2012 Trends in primary particulate matter emissions from Canadian agriculture J. Air Waste Manage. Assoc. 62 757–47

Paulot F and Jacob D J 2014 Hidden cost of U.S. agricultural exports: particulate matter from ammonia emissions Environ. Sci. Technol. 48 903–8

Paulot F, Jacob D J, Pinder R W, Bash J O, Travis K and Henze D K 2014 Ammonia emissions in the United States, European Union, and China derived by high-resolution inversion of ammonium wet deposition data: interpretation with a new agricultural emissions inventory (MASAGE_NH3) J. Geophys. Res. 119 4343–64

Pellerin P and Fernández R J 2018 Crop intensification, land use, and on-farm energy-use efficiency during the worldwide spread of the green revolution Proc. Natl. Acad. Sci. USA 115 2335–40

Pelletier N 2015 Life Cycle Thinking, measurement and management for food system sustainability Environ. Sci. Technol. 49 7515–9

Penndrill F, Persson U M, Godar J, Kastner T, Moran D, Schmidt S and Wood R 2019 Agricultural and forestry trade drives large share of tropical deforestation emissions Glob. Environ. Change 56 1–10

Penfold B M, Sullivan D C, Reid S B and Chinkin L R 2005 Development of agricultural dust emission inventories for the Central States Regional Air Planning Association 14th U.S. EPA Annu. Emiss. Invent. Conf. (available at: www.epa.gov/ttn/chief/conference/e114/session7/reid.pdf) (Accessed May 2020)
Pervez S, Verma M, Tiwari S, Chakrabarty R K, Watson J G, Chow J C, Panicker A S, Deb M K, Siddiqui M N and Pervez Y F 2019 Household solid fuel burning emission characterization and activity levels in India Sci. Total Environ. 654 493–504

Petersen R et al 2016 Mapping tree plantations with multispectral imagery: preliminary results for seven tropical countries, World Resources Institute, Washington, DC

Pinder R W, Adams P J and Pandis N S 2007 Ammonia emission controls as a cost-effective strategy for reducing atmospheric particulate matter in the Eastern United States Environ. Sci. Technol. 41 380–6

Pirog R, van Pelt T, Enshayan K and Cook E 2001 Food, fuel, and freeways: an Iowa perspective on how far food travels, fuel usage, and greenhouse gas emissions, Leopold Center for Sustainable Agriculture, Iowa State University, Ames (available at: https://lib.dr.iastate.edu/leopold_pubs/papers/3/)

Pfister J 2018 Piercing the haze Science 361 1060–3

Ponisio L C, M’gonigle L K, Mace K C, Palomino J, de Valpine P and Kremen C 2015 Diversification practices reduce organic to conventional yield gap Proc. R. Soc. B 282 20141396

Poore J and Nemeck T 2018 Reducing food’s environmental impacts through producers and consumers Science 360 987–91

Pope C A, Thun M J, Namboodiri M M, Dockery D W, Evans J S, Speizer F E and Heath C W 1995 Particulate air pollution as a predictor of mortality in a prospective study of US adults Am. J. Respir. Crit. Care Med. 151 74

Pope C A, Coleman N, Pond Z A and Burnett R T 2019 Fine particulate air pollution and human mortality: 25 + y ears of cohort studies Environ. Res. 183 108924

Porter S D, Reay D S, Higgins F and Bomberg E 2016 A half-century of production-phase greenhouse gas emissions from food loss & waste in the global food supply chain Sci. Total Environ. 571 721–9

Pouliot G, Rao V, McCarty J L and Soja A 2017 Development of the crop residue and rangeland burning in the 2014 National Emissions Inventory using information from multiple sources J. Air Waste Manage. Assoc. 67 613–22

Pozzer A, Tsipmpidi A P, Karydis V A, De Meij A and Lelieveld J 2019 Impacts of household sources on air pollution at village and regional scales in India Environ. Sci. Total Environ. 655 473–81

Punger E M and West J 2013 The effect of grid resolution on estimates of the burden of ozone and fine particulate matter on premature mortality in the USA Air Qual. Atmos. Health 6 563–73

Ramankutty N, Mehrabi Z, Waha K, Jarvis L, Kremen C, Herrero M and Riebsame L H 2018 Trends in global agricultural land use: implications for environmental health and food security Annu. Rev. Plant Biol. 69 789–815

Ravindra K, Singh T and Mor S 2019 Emissions of air pollutants from primary crop residue burning in India and their mitigation strategies for cleaner emissions J. Clean. Prod. 208 261–77

Reddington C L, Butt E W, Ridley D A, Artaxo P, Morgan W T, Coe H and Spracklen D V 2015 Air quality and human health improvements from reductions in deforestation-related fire in Brazil Nat. Geosci. 8 768–71

Reddington C L, Comibear L, Knote C, Silver B J, Li Y J, Chan C K, Arnold S R and Spracklen D V 2019 Exploring the impacts of anthropogenic emission sectors on PM10 and human health in South and East Asia Atmos. Chem. Phys. 19 11887–910

Reddington C L, Yoshioka M, Balasubramanian R, Ridley D, Toh Y Y, Arnold S R and Spracklen D V 2014 Contribution of vegetation and peat fires to particulate air pollution in Southeast Asia Environ. Res. Lett. 9 094006

Rehfuess E A, Bruce N G and Smith K R 2011 Solid fuel use: health effect Environ. Heal. Hul. 5 150161

Robinson A L, Apte J S, Marshall J D, Robinson A L and Presto A A 2018 Impact of outdoor air quality: elevated organic aerosol mass from restaurant cooking with neighborhood-scale plume extents Environ. Sci. Technol. 52 9285–94

Roden C A, Bond T C, Conway S, Osintro Pinel A B, MacCartny N and Still D 2009 Laboratory and field investigations of particulate and carbon monoxide emissions from traditional and improved cookstoves Atmos. Environ. 43 1170–81

Roos S M, Spivey M D, Lindquist H C, Hemmer P, Dorado E and Hunter R 2004 National Emissions Inventory for commercial cooking (available at: www3.epa.gov/ttn/chief/conference/ei13/pointarea/roe.pdf) (Accessed September 2019)

Rogge W F, Cass G R, Hildemann L M, Mazurek M A and Simoneit B R T 1991 Sources of fine organic aerosol. 1. Charbroilers and meat cooking operations Environ. Sci. Technol. 25 1112–25

Rooney B et al 2019 Impacts of household sources on air pollution at village and regional scales in India Atmos. Chem. Phys. 19 7719–42

Rose S M, Silver E S, Gu P , Apte J S, Marshall J D, Robinson A L and Presto A A 2018 Impact of outdoor air quality: elevated organic aerosol mass from restaurant cooking with neighborhood-scale plume extents Environ. Sci. Technol. 52 9285–94

Rooney B et al 2019 Quantifying high-resolution spatial variations and local source impacts of urban ultrafine particle concentrations Sci. Total Environ. 655 473–81

Schiefler L D et al 2016 Interannual variability of ammonia concentrations over the United States: sources and implications Atmos. Chem. Phys. 16 12305–38

Schmitt E, Keech D, Maye D, Barjolle D and Harris N L 2019 Reducing tropical deforestation-related fire in Brazil Environ. Sci. Technol. 53 4765–74

Schraufnagel D E 2020 The health effects of ultrafine particles Exp. Mol. Med. 52 311–7

Seinfeld J H and Pandis S N 2016 Atmospheric Chemistry and Physics: From Air Pollution to Climate Change

Shah R U, Robinson E S, Gu P , Apte J S, Marshall J D, Robinson A L and Presto A A 2018 Impact of outdoor air quality: elevated organic aerosol mass from restaurant cooking with neighborhood-scale plume extents Environ. Sci. Technol. 52 9285–94

Sharma G, Sinha B, Pallavi, Hakkim H, Chandra B P, Kumar A and Sinha V 2019 Gridded emissions of CO, NOx, SO2, CO2, NH3, HCl, CH4, PM10, PM2.5, BC, and NMVOC from open municipal waste burning in India Environ. Sci. Technol. 53 4765–74

Shen G et al 2015 Pollutant emissions from improved coal- and wood-fueled cookstoves in rural households Environ. Sci. Technol. 49 6590–8
Shen G, Gaddam C K, Ebersviller S M, Vander Wal R L, Williams C, Faircloth J W, Letter J J and Hays M D 2017 A laboratory comparison of emission factors, number size distributions, and morphology of ultrafine particles from 11 different household cookstove-fuel systems Environ. Sci. Technol. 51 6522–32

Shi L, Zanobetti A, Klooog I, Coull B A, Koutrakis P, Melly S J and Schwartz J D 2016 Low-concentration PM$_{2.5}$ and mortality: estimating acute and chronic effects in a population-based study Environ. Health Perspect. 124 46–52

Shiraiwa M et al 2017 Aerosol health effects from molecular to global scales Environ. Sci. Technol. 51 1354–67

Shupler M, Godwin W, Frostad J, Gustafson P, Arku R E and Brauer M 2018 Global estimation of exposure to fine particulate matter (PM$_{2.5}$) from household air pollution Environ. Int. 120 354–63

Sidhu M K, Ravindra K, Mor S and John S 2017 Household air pollution from various types of rural kitchens and its exposure assessment Sci. Total Environ. 586 419–29

Silva R A, Adelman Z, Fry M M and West J J 2016 The impact of individual anthropogenic emissions sectors on the global burden of human mortality due to ambient air pollution Environ. Health Perspect. 124 1776–84

Slattery B 2005 National Emission Inventory—ammonia emissions from animal husbandry (available at: www.epa.gov/ttn/chief/net/2002inventory.htm) (Accessed July 2019)

Smith A, Watkiss P, Tweddle G, McKinnon A, Browne M, Hunt A, Treleven C, Nash C and Cross S 2005 The validity of food miles as an indicator of sustainable development vol ED50254 (available at: http://library.universitycoop.coop/Food/DERFA Food _Miles_Report.pdf) (Accessed August 2020)

Smith K R et al 2014 Millions dead: how do we know and what does it mean? Methods used in the comparative risk assessment of household air pollution Annu. Rev. Public Health 35 185–206

Smith K R and Pillarretti A 2017 Household air pollution from solid cookfuels and its effects Health Injury Prevention and Environmental Health ed C N Mock, R Nugent and O Kobusingye et al (Washington, DC: The World Bank) ([https://doi.org/10.1596/978-1-4648-0522-6_ch7])

Solazzo E et al 2017 Evaluation and error apportionment of an ensemble of atmospheric chemistry transport modeling systems: multivariable temporal and spatial breakdown Atmos. Chem. Phys. 17 3001–54

Sommer S G, Schjoerring J K and Dennead O T 2004 Ammonia emission from mineral fertilizers and fertilized crops Adv. Agron. 2113 557–622

Sonarkar P R and Chaurasia A S 2019 Thermal performance of three improved biomass-fired cookstoves using fuel wood, wood pellets and coconut shell Environ. Dev. Sustain. 21 1426–49

Song X P, Hansen M C, Stehman S V, Potapov P V, Tyukavina A, Vermote E F and Townsend J R 2018 Global land change from 1982 to 2016 Nature 560 639–43

Springmann M et al 2018a Options for keeping the food system within environmental limits Nature 562 519–25

Springmann M, Godfray H C J, Rayner M and Scarborough P 2016 Analysis and valuation of the health and climate change co-benefits of dietary change Proc. Natl Acad. Sci. USA 113 4146–51

Springmann M, Mason-D’Croz D, Robinson S, Wiebe K, Godfray H C J, Rayner M and Scarborough P 2017 Mitigation potential and global health impacts from emissions pricing of food commodities Nutr. Clim. Change 7 69–74

Springmann M, Wiebe K, Mason-D’Croz D, suber T B, Rayner M and Scarborough P 2018b Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail Lancet Planet. Health 2 e451–58

Story M, Kaphingst K M, Robinson-O’Brien R and Glanz K 2008 Creating healthy food and eating environments: policy and environmental approaches Annu. Rev. Public Health 29 253–72

Sun F, Dai Y and Yu X 2017 Air pollution, food production and food security: a review from the perspective of food system J. Integr. Agric. 16 2945–62

Sutton M A, Oenema O, Erisman J W, Leip A, van Grinsven H and Wininater W 2011 Too much of a good thing Nature 472 157–61

Pande G, Alok C C and Lai O-M 2012 Food uses of palm oil and its components Palm Oil—Production, Processing, Characterization, and Uses (AOCs Press) ([https://doi.org/10.1016/B978-0-9818936-9-3.50022-8])

Tao S et al 2016 Residential Solid Fuel Combustion and Impacts on Air Quality and Human Health in Mainland China (Washington DC: Global Alliance for Clean Cook Stoves) (available at: https://www.cleancooksgivingalliance.org/binary-data/RESOURCE/file/000/000/492-1.pdf)

Tessum C W et al 2019 Inequity in consumption of goods and services adds to racial—ethnic disparities in air pollution exposure Proc. Natl Acad. Sci. 116 201818859

Tessum C W, Hill J D and Marshall J D 2017 InMAP: a model for air pollution interventions PLoS One 12 9281–321

Tester A W 2020 Deforestation in the global South: assessing uneven environmental improvements 1993–2013 Sociol. Percep. 4 164–84

Thakrar S K et al 2020 Reducing mortality from air pollution in the United States by targeting specific emission sources Environ. Sci. Technol. Lett. 15 639–45

Thompson T M, Saari R K and Selin N E 2014 Air quality resolution for health impact assessment: influence of regional characteristics Atmos. Chem. Phys. 14 969–78

Ti C, Xia L, Chang S X and Yan X 2019 Potential for mitigating global agricultural ammonia emission: a meta-analysis Environ. Pollut. 245 141–8

Tilman D, Balzer C, Hill J D and Befort B L 2011 Global food demand and the sustainable intensification of agriculture Proc. Natl Acad. Sci. USA 108 20260–4

Tilman D and Clark M 2014 Global diets link environmental sustainability and human health Nature 515 518–22

Timmer M, Erumban A, Francois J and Genty A 2012 The World Input-Output Database (WIOD): Contents, Sources and Methods (available at: www.wiod.org) (Accessed July 2020)

Todd J E 2017 Changes in consumption of food away from home and intakes of energy and other nutrients among US working-age adults, 2005–2014 Public Health Nutr. 20 3238–46

Torkmahalleh M A, Gorjinezhad S, Unluvecek H S and Hopke P K 2017 Review of factors impacting emission/concentration of cooking generated particulate matter Sci. Total Environ. 586 1046–56

Tumwesige V, Okello G, Semple S and Smith J 2017 Impact of partial fuel switch on household air pollutants in sub-Saharan Africa Environ. Pollut. 231 1021–9

Uman L S 2011 Systematic reviews and meta-analyses J. Can. Acad. Child. Adolesc. Psychiatry 20 57–59

UNEP 2017 Protocol to the 1979 convention on long-range transboundary air pollution to abate acidification, eutrophication and ground-level ozone: annex II emission reduction commitments (United Nations Economic Commission for Europe) (available at: www.unice.org/fileadmin/DAM/en/documents/2017/AIR/Gothenburg_ Protocol/Annex_II_and_III_updated_clean.pdf) (Accessed August 2020)

Upham P, Dendler L and Bleda M 2011 Carbon labelling of grocery products: public perceptions and potential emissions reductions J. Clean. Prod. 19 348–55

US EPA 1995 Compilation of air pollutant emission factors, AP-42, Volume 1: stationary point & area sources (available at: www.epa.gov/air-emissions-factors-and-quanitification/ap-42-compilation-air-emissions-factors#5thed) (Accessed May 2019)
US EPA 2011 Reactive Nitrogen in the United States: An Analysis of Input, Flows, Consequences and Management Options: A Report of the EPA Science Advisory Board EPA-SAB-11-013

US EPA 2017 Overview of the Clean Air Act and air pollution (available at: www.epa.gov/clean-air-act-overview) (Accessed July 2020)

US EPA 2018 2014 National Emissions Inventory, version 2, Technical Support Document (available at: www.epa.gov/sites/production/files/2018-07/documents/nemis2014v2_tsd_05fla2018.pdf) (Accessed March 2020)

Van Damme M, Clarisse L, Whitburn S, Haji-Lazaro J, Hurtmans D, Clerbaux C and Coheur P F 2018 Industrial and agricultural ammonia point sources exposed Nature 564 99–103

Van den Bergh R et al 2017 Global fire emissions estimates during 1997–2016 Earth Syst. Sci. Data 9 697–720

Van der Werf G R, Randerson J T, Giglio L, Collatz G J, Mu M, Kasibhatla P S, Morton D C, Defries R S, Jin Y and van Leeuwen T T 2010 Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009) Atmos. Chem. Phys. 10 11170–35

Van Donkelaar A, Martin R V, Brauer M, Hsu N C, Kahn R A, Levy R C, Lyapustin A, Sayer A M and Winker D M 2016 Global estimates of fine particulate matter using a combined geophysical-statistical method with information from satellites, models, and monitors Environ. Sci. Technol. 50 3762–72

Van Grinsven H M J, Holland M, Jacobsen B H, Klimont Z, Levy R C, Lyapustin A, Sayer A M and Winker D M 2016 Global estimates of fine particulate matter using a combined geophysical-statistical method with information from satellites, models, and monitors Environ. Sci. Technol. 47 3571–5579

Van Iersel M K, Cassman K G, Grassi P, Wolf J, Tittonell P and Hochman Z 2013 Yield gap analysis with local to global relevance—a review E. Crop. Res. 143 4–17

Vermeulen S J, Campbell B M and Ingram J S I 2012 Climate change and food systems Annu. Rev. Environ. Resour. 37 195–222

Wakeland W, Choltite S and Venkat K 2012 Food transportation issues and reducing carbon footprint Green Technologies in Food Production and Processing, Food Engineering Series ed J Boye and Y Arcand (New York: Springer) pp 211–34

Wang F, Li Z, Zhang K, Di B and Hu B 2016 An overview of non-road equipment emissions in China Atmos. Environ. 132 283–9

Wang K and Zhang Y 2014 3D agricultural air quality modeling: impacts of NH3/H2S gas-phase reactions and bi-directional exchange of NH3 Atmos. Environ. 98 354–70

Wang S and Zeng Y 2018 Ammonia emission mitigation in food waste composting: a review Bioresour. Technol. 248 13–19

Warner J X, Dickerson R R, Wei Z, Stow L I, Wang Y and Liang Q 2017 Increased atmospheric ammonia over the world’s major agricultural areas detected from space Geophys. Res. Lett. 44 2875–84

Weagle C L et al 2018 Global sources of fine particulate matter: interpretation of PM2.5 chemical composition observed by SPARtan using a global chemical transport model Environ. Sci. Technol. 52 11670–81

Webb J, Pain B, Bittman S and Morgan J 2010 The impacts of manure application methods on emissions of ammonia, nitrous oxide and on crop response—a review Agric. Ecosyst. Environ. 137 39–46

Weber C L and Matthews H S 2008 Food-miles and the relative climate impacts Environ. Sci. Technol. 42 3508–13

West J J et al 2016 What we breathe impacts our health: improving understanding of the link between air pollution and health Environ. Sci. Technol. 50 4895–904

WHO 2016 Burning Opportunity: Clean Household Energy for Health, Sustainable Development, and Wellbeing of Women and Children (available at: www.afro.who.int/sites/default/files/2017-06/9789241565233_eng.pdf) (Accessed June 2020)

WHO 2018 Global Nutrition Report 2018 (available at: https://globalnutritionreport.org/reports/global-nutrition-report-2018/) (Accessed October 2020)

Wiedinmyer C, Yokelson R J and Gullett B K 2014 Global emissions of trace gases, particulate matter, and hazardous air pollutants from open burning of domestic waste Environ. Sci. Technol. 48 9523–30

Willott W et al 2019 Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems Lancet 393 447–92

Wollenberg E et al 2016 Reducing emissions from agriculture to meet the 2 °C target Glob. Change Biol. 22 3839–64

World Bank 2018a What a Waste 2.0 Database What a Waste 2.0 A Glob. Snapshot Solid Waste Manag. to 2050 (available at: https://datacatalog.worldbank.org/dataset/what-waste-global-database) (Accessed November 2019)

World Bank 2018b World Development Indicator Agric. For. fishing, value added (% GDP) (available at: https://data.worldbank.org/indicator) (Accessed June 2020)

World Bank 2020 Population, Total DataBank (available at: https://databank.worldbank.org/home.aspx) (Accessed June 2020)

World Resources Institute 2014 Global Forest Watch (available at: www.globalforestwatch.org) (Accessed June 2020)

Xu P, Koloutsou-Vakakis S, Rood M J and Luan S 2017 Long-term fine particulate matter exposure and mortality in China: reconciling bottom-up and top-down estimates Atmos. Chem. Phys. 339 355–1–36

Zhang X et al 2017a Characterization of trace elements and ions in PM2.5 and PM10 emitted from animal confinement buildings Atmos. Environ. 152 667–78

Zhang L, Chen Y, Zhao Y, Henze D K, Zhu L, Song Y, Paulot F, Xue L, Liu G, Parfitt J, Liu X, van Herpen E, Stenmarck Å, O’Connor C, Östergren K and Cheng S 2017 Missing food, missing data? A critical review of global food losses and food waste data Environ. Sci. Technol. 51 6618–33

Yang X, Wang X, Zhang Y, Lee J, Su J and Gates R S 2011 World Bank 2018b World Development Indicator Agric. For. fishing, value added (% GDP) (available at: https://datacatalog.worldbank.org/dataset/what-waste-global-database) (Accessed November 2019)

Yang L, Liu G, Parfitt J, Liu X, van Herpen E, Stenmarck Å, O’Connor C, Östergren K and Cheng S 2017 Missing food, missing data? A critical review of global food losses and food waste data Environ. Sci. Technol. 51 6618–33

Yang X, Wang X, Zhang Y, Lee J, Su J and Gates R S 2011 Characterization of trace elements and ions in PM2.5 and PM10 emitted from animal confinement buildings Atmos. Environ. 45 7096–104

Yin P et al 2012 Long-term fine particulate matter exposure and nonaccidental and cause-specific mortality in a large national cohort of Chinese men Environ. Health Perspect. 125 117002–11

Zhang B, Tian H, Lu C, Dangal S R S, Yang J and Pan S 2017a Global manure nitrogen production and application in cropland during 1860–2014: a 5 arcmin gridded global database for earth system modeling Earth Syst. Sci. Data 9 667–78

Zhang L, Chen Y, Zhao Y, Henze D K, Zhu L, Song Y, Paulot F, Liu X, Pan Y and Huang B 2017b Agricultural ammonia emissions in China: reconciling bottom-up and top-down estimates Atmos. Chem. Phys. 339 355–1–36

Zhang X et al 2017c Air pollution in China: a national assessment. Environ. Sci. Technol. 51 12089–96

Zhao B et al 2018 Change in household fuels dominates the decrease in PM2.5 exposure and premature mortality in China in 2005–2015 Proc. Natl. Acad. Sci. USA 115 12401–6

Zhou Z, Dionisio K L, Arku R E, Quaye A, Hughes A F, Vallarino J, Spengler J D, Hill A, Agyei-Mensah S and Hochman Z 2013 Yield gap analysis with local to global relevance—a review E. Crop. Res. 143 4–17

Zhu L, Henze D K, Zhu L, Song Y, Paulot F, Liu X, Pan Y and Huang B 2017b Agricultural ammonia emissions in China: reconciling bottom-up and top-down estimates Atmos. Chem. Phys. 339 355–1–36

Zhu L, Henze D K, Bash J O, Cady-Pereira K E, Shephard M W, Luo M and Paulot F 2015b Sources and impacts of ammonia NH3: current understanding and frontiers for modeling, measurements, and remote sensing in North America Curr. Pollut. Rep. 1 95–116

Zhu L, Henze D K, Bash J O, Cady-Pereira K E, Shephard M W, Luo M, Paulot F and Capps S 2015a Global evaluation of ammonia bidirectional exchange and livestock diurnal variation schemes Atmos. Chem. Phys. 15 12823–43