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Air-quality-related health damages of maize

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Agriculture is essential for feeding the large and growing world population, but it can also generate pollution that harms ecosystems and human health. Here, we explore the human health effects of air pollution caused by the production of maize—a key agricultural crop that is used for animal feed, ethanol biofuel and human consumption. We use county-level data on agricultural practices and productivity to develop a spatially explicit life-cycle-emissions inventory for maize. From this inventory, we estimate health damages, accounting for atmospheric pollution transport and chemistry, and human exposure to pollution at high spatial resolution. We show that reduced air quality resulting from maize production is associated with 4,300 premature deaths annually in the United States, with estimated damages in monetary terms of US$39 billion (range: US$14–64 billion). Increased concentrations of fine particulate matter ($PM_{2.5}$) are driven by emissions of ammonia—a $PM_{2.5}$ precursor—that result from nitrogen fertilizer use. Average health damages from reduced air quality are equivalent to US$121 t^{-1} of harvested maize grain, which is 62% of the US$195 t^{-1} decadal average maize grain market price. We also estimate life-cycle greenhouse gas emissions of maize production, finding total climate change damages of US$4.9 billion (range: US$1.5–7.5 billion), or US$15 t^{-1} of maize. Our results suggest potential benefits from strategic interventions in maize production, including changing the fertilizer type and application method, improving nitrogen use efficiency, switching to crops requiring less fertilizer, and geographically reallocating production.

Agriculture provides the world with food but also damages the environment in ways that harm human health. It is a major contributor to climate change[1], water pollution[2] and degraded air quality[3,4], with the potential for even greater impact as demand for food increases from a growing and more affluent global population[5]. Understanding the current environmental effects of agriculture, and linking them to dietary choices, is a critical challenge for the coming century[6]. We explore the human health effects of air pollution caused by the production of maize—a key agricultural crop in the United States that is used for animal feed, ethanol biofuel and human consumption. Our focus is on the contribution of maize production to increased atmospheric concentrations of $PM_{2.5}$—a major cause of premature mortality in the United States and globally[7–9]. We also estimate the climate change damages of US maize production from greenhouse gas (GHG) emissions.

We consider air emissions of pollutants from farms and the supply chains that produce the chemical and energy inputs used in agricultural crop production. We compile geographically explicit county- and subcounty-specific data on maize production, inputs and yields (Fig. 1 and Supplementary Dataset 1), and on maize-related emissions of pollutants that contribute to atmospheric $PM_{2.5}$. These emissions include primary $PM_{2.5}$, which is released from fuel combustion and dust, and secondary $PM_{2.5}$ precursors that form $PM_{2.5}$ in the atmosphere, including ammonia (NH_3), sulfur oxides (SO_x), nitrogen oxides (NO_x) and volatile organic compounds (VOCs). We produce a spatially explicit emissions inventory[10,11] of primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursors (Fig. 2), from which we estimate maize-related increases in the atmospheric concentration of $PM_{2.5}$, spatial transport of this $PM_{2.5}$ with air movement patterns, exposure of populations to this $PM_{2.5}$, and resulting health and economic effects[12]. We also perform a simultaneous accounting of maize-related emissions of GHGs, which include carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and black carbon.

We find that maize production in the United States causes an estimated 4,300 cases annually of premature mortality due to $PM_{2.5}$ (Fig. 3 and Table 1). Geographically in the United States, increased concentrations of $PM_{2.5}$ (Fig. 3a), mortality (Fig. 3b) and county contribution to mortality (Fig. 3c) are located in the 'Corn Belt'[13], where most US maize production occurs (Fig. 1a). The top 5 maize-producing states (Iowa, Illinois, Nebraska, Minnesota and Indiana) are responsible for 61% of US maize production and 54% of instances of maize-dependent premature mortality (2,313 deaths). Maize grown in Illinois, the second-largest producing state (15% of US production), results in the most deaths annually of all states (795 deaths, or 18% of the total).

$PM_{2.5}$-related human health damages per tonne of maize produced vary widely by location (Figs. 3d and 4). High per-tonne damages come from maize produced in the Eastern Corn Belt (for example, Indiana, Michigan and Ohio), near major Central Corn Belt metropolitan areas (for example, Chicago, Milwaukee and Minneapolis/Saint Paul) and to the east and south of the Corn Belt (for example, Pennsylvania, North Carolina and Texas). These higher-than-average impacts result from: (1) closer proximity of farms to the high population densities of urban centres; (2) lower yields than in the highest maize-producing regions (Fig. 1b); and (3) higher use of animal manures as fertilizer, which can result in higher NH_3 emissions than synthetic fertilizers. Conversely,

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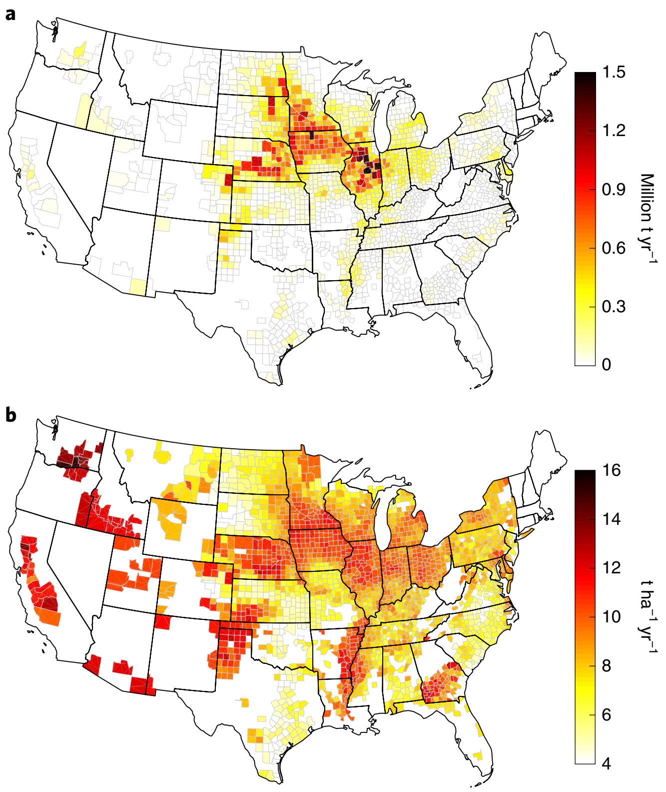

Fig. 1 | County-level US maize production. a, Production. **b**, Yield. Averages from 2010–2014 are shown[15].

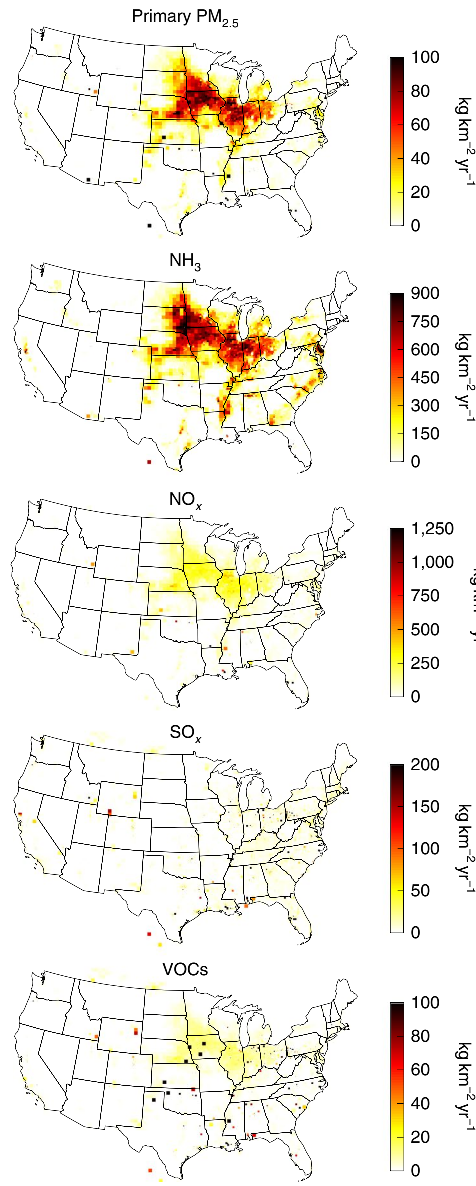

Fig. 2 | Emissions per square kilometre of primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursors from US maize production. Emissions are shown for primary $PM_{2.5}$ and the secondary $PM_{2.5}$ precursors NH_3, NO_x, SO_x and VOCs. Emission sources include on-farm and supporting supply chain activities. Isolated dark spots represent major sources of supply chain emissions other than farm fields, including fertilizer production facilities and power plants.

production in rural areas of the Central and Western Corn Belt tends to have the lowest damages per tonne.

The dominant contributor to maize production-related $PM_{2.5}$ concentrations is emissions of NH_3 from synthetic nitrogen fertilizer and manure application (Fig. 5), which account for 71% of attributable deaths. Minor contributors to increased $PM_{2.5}$ concentrations include NO_x and primary $PM_{2.5}$ from fuel combustion by farm equipment, and primary $PM_{2.5}$ dust from cultivation. On average, 86% of the human health damages from maize production are from on-farm activities; the rest are from upstream supply chain processes, primarily the production and transport of fertilizer.

At a value of statistical life (VSL) of US$9.1 million (2017$) (range: US$3.3–14.8 million), which measures willingness to pay to reduce the risk of death[14], total annual $PM_{2.5}$-related damages from maize production in the United States are US$39 billion (range: US$14–64 billion). Production-weighted $PM_{2.5}$-related damages, which vary widely depending on production location (Fig. 6), average US$121 t^{-1} of harvested maize grain, or 62% of the US national average market price of maize for the past decade[15] of US$195 t^{-1}.

The economic damages of $PM_{2.5}$ from maize production exceed those from its GHG emissions. At a social cost of carbon (SCC) of US$43 (2017$) per tonne of CO_2e GHGs (range: US$13–67)[16], the total annual GHG-related damages of the 112 million tonnes of CO_2e GHGs resulting from US maize production are US$4.9 billion (range: US$1.5–7.5 billion). Average GHG damages are US$15 t^{-1} of maize (Fig. 6), dominated by emissions of CO_2 and N_2O. Consistent with previous work[11], the highest per-tonne damages occur on the periphery of and beyond the Corn Belt (Fig. 7). Total annual average $PM_{2.5}$ + GHG-related damages are US$136 t^{-1} (Fig. 6), or 70% of the national decadal average maize market price[15]. In many regions of the United States, the $PM_{2.5}$ + GHG-related damage costs of producing maize exceed its market value, including in 40% of maize-growing counties and 39% of maize-growing states.

Maize is a dominant crop on the US agricultural landscape and a major contributor to premature mortality from reduced air quality—largely from NH_3 emissions caused by nitrogen fertilization. Maize receives nearly half of the nitrogen fertilizer applied in the United States[17], and is a major source of NH_3 emissions in the United States, responsible for ~21% of emissions from agriculture and ~18% of emissions from all sources[18]. Our work suggests the importance of targeted emissions reductions, especially of NH_3, in areas of high impact or low production efficiency for reducing the human health impacts of maize production. NH_3 reductions of 16–88% can be achieved by the use of precision agriculture, as well as optimum fertilizer types and application methods[19].

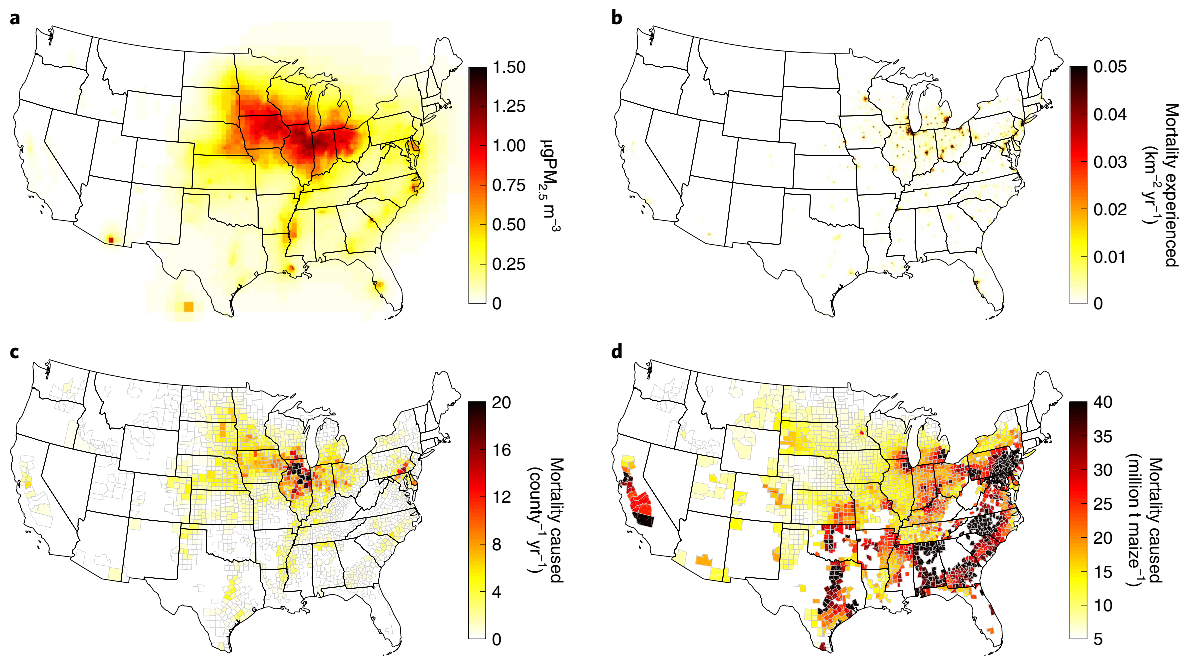

Fig. 3 | $PM_{2.5}$ impacts of US maize production. a, Atmospheric total $PM_{2.5}$ (primary $PM_{2.5}$ + secondary $PM_{2.5}$) concentrations attributable to US maize production. **b**, Annual mortality per squared kilometre from total $PM_{2.5}$ attributable to US maize production (that is, where people die as a result of US maize production). **c**, County-level annual mortality from total $PM_{2.5}$ attributable to US maize production (that is, how many people, somewhere in the United States, die annually from all maize production in a given county). **d**, County-level mortality per million tonnes of maize produced in a given county (that is, how many people, somewhere in the United States, die annually as a result of the production of one million tonnes of maize in a given county).

Table 1 | Maize production, total mortality and mortality per million tonnes by state

State	10^6 t maize	Deaths	Deaths per 10^6 t maize
Iowa	55.4	539	9.7
Illinois	49.0	795	16.2
Nebraska	38.1	269	7.1
Minnesota	32.1	245	7.6
Indiana	22.7	465	20.5
South Dakota	17.0	172	10.1
Ohio	13.8	288	20.9
Kansas	12.7	126	9.9
Wisconsin	11.9	168	14.1
Missouri	10.2	145	14.1
Michigan	8.5	145	17.1
North Dakota	8.2	55	6.7
All others	42.8	897	21.0
Total	322.3	4,309	13.4

Annual average production from USDA for the years 2010–2014[17]. Deaths are the estimated total deaths (that is, occurring anywhere in the United States) attributable to maize production in the specific state.

Such practices may also increase nitrogen use efficiency, thereby providing an economic benefit to farmers[20]. Targeted placement of maize production could include providing incentives for farmers in high-damage-causing regions to switch to less fertilizer-intensive crops. Incentives focused on rewarding good practices in the right locations could offer large benefits per tonne of maize produced.

The maize production damage costs considered here are only part of the air pollution damages and the full environmental and health costs of maize. Maize-dependent air quality reductions contribute to morbidity-related medical costs and reduced quality of life. Similarly, the NO_x and VOCs emitted from maize production contribute to ground-level ozone formation that impacts environmental and health costs. Our focus here has been on the production of maize, but nearly all maize is transformed before its final use by consumers. Nearly 90% of maize grown in the United States is used for animal feed or ethanol biofuel[21], both of which lead to further emissions of primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursors, as well as GHGs[18,22]. Notably, 55% of US emissions of NH_3 are from animal production. Approximately 10% of maize grown in the United States is consumed as sweeteners, starch, cereals or beverages, which require further processing, transport, storage and preparation, all of which directly or indirectly release air pollution. For these reasons, our estimates more reflect maize as a commodity than maize as a food.

Growing recognition of the environmental damage caused by agriculture, coupled with an increased desire by consumers to eat healthier and less impactful diets, has spurred interest in linking the nutritional and environmental effects of foods. Recent work has revealed the environmental benefits of healthier dietary choices, yet the dominant environmental focus has been on climate change and ecosystem effects rather than on how crop-dependent environmental degradation affects human health[23–26]. This is despite reduced air quality being known to be the single largest environmental health risk factor globally[27]. Although agriculture is known to impact air quality[28–30], our work shows that maize-dependent reductions in air quality are a surprisingly large source of harm to human health. The approach we have taken here can be extended to other food crops, animal agriculture and other countries, to better understand the full suite of health consequences of dietary choices.

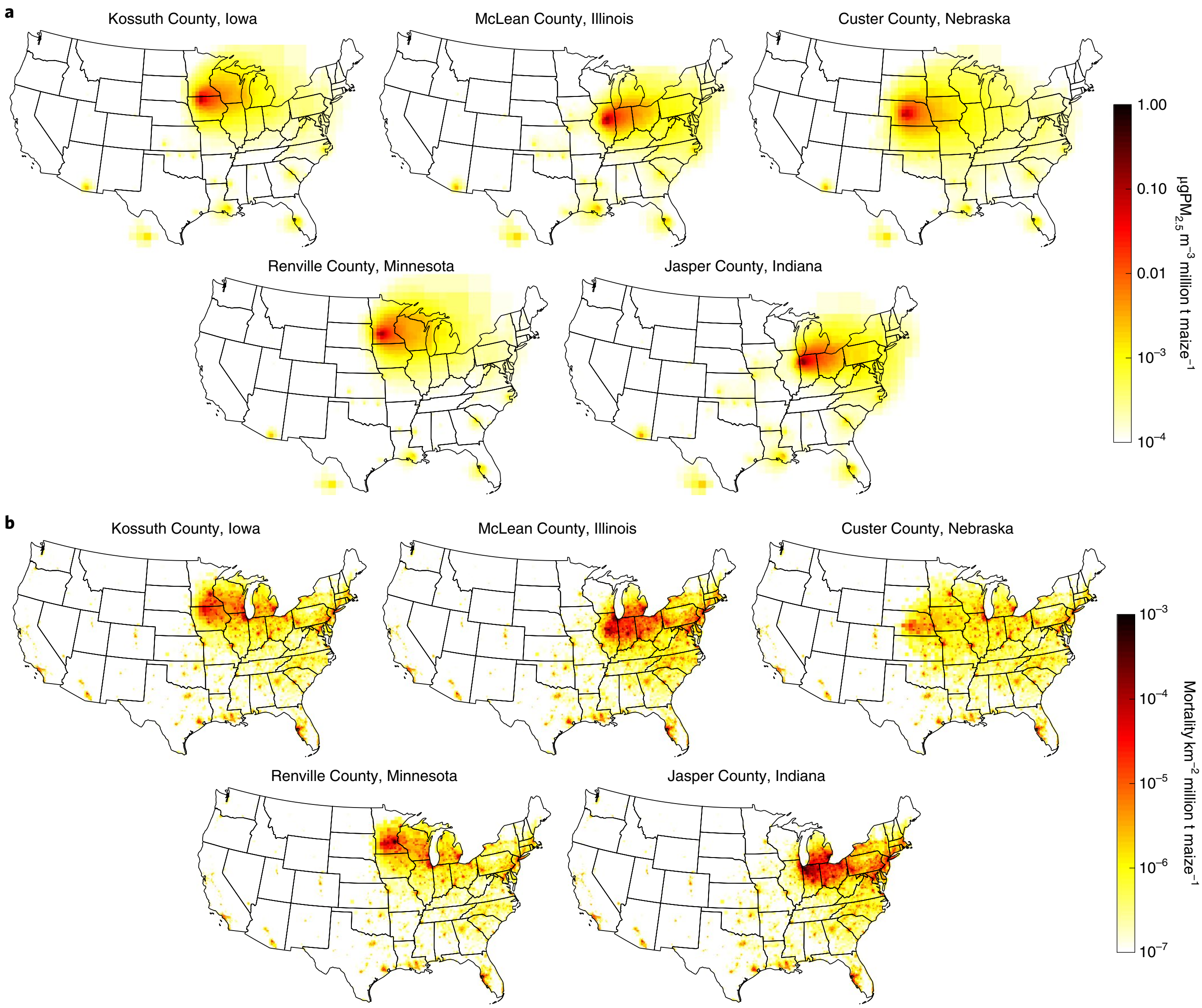

Fig. 4 | Illustrative results of $PM_{2.5}$ impact assessment using the top maize-producing county in each of the top five maize-producing states. a, Atmospheric total $PM_{2.5}$ concentrations attributable to on-farm and supporting supply chain processes for maize grown in a single county. Emissions attributable to maize produced in a given county may occur outside that county (for example, from fertilizer production). **b**, Mortality attributable to total $PM_{2.5}$ concentrations in **a**. Further examples of this relationship between total $PM_{2.5}$ concentrations and increased mortality as estimated by InMAP are shown for the 6th–20th top maize-producing states in Supplementary Figs. 1–3.

Methods

Emissions inventory. Geographically explicit emissions inventories of pollutants contributing to increased atmospheric concentrations of $PM_{2.5}$ (primary $PM_{2.5}$, SO_x, NO_x, VOCs and NH_3) and GHGs (CO_2, N_2O, CH_4 and black carbon) were compiled using a modified version of the GREET.net 2015 (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) life-cycle assessment model from Argonne National Laboratory[31]. This version (GREET-Chemical, Spatial, and Temporal (GREET-cst)) incorporates spatial data on emissions sources[10,18,32–34], tracks NH_3 emissions by linking each unit process in GREET to a process-specific emissions profile from the National Emissions Inventory (NEI)[18] developed by the US Environmental Protection Agency, and estimates fugitive dust release from agricultural activities[34–36]. For the analysis presented here, GREET-cst was run once for each of the top 2,000 maize-producing counties, which together account for 99.9% of US maize production[15]. In each run, GREET-cst was populated with county-specific agricultural data for 2010–2014 (Supplementary Dataset 1), as described in the following section.

The output of each GREET-cst run was a spatially explicit national inventory of emissions of each pollutant attributable to maize production in a given county, including on-farm emissions and emissions of upstream supply chain processes including fuel, electricity, and agrichemical production, transportation and distribution. Emissions attributable to maize production in a given county need not occur within that county (for example, emissions from fertilizer production facilities, which are often sited far from where the maize is grown). For each $PM_{2.5}$-related pollutant (primary $PM_{2.5}$, SO_x, NO_x, VOCs and NH_3), the output of all 2,000 GREET-cst runs was aggregated to produce an emissions inventory for US maize production and its supporting supply chains (Fig. 2). These inventories were used as inputs into the air quality modelling and impact assessment, as described in the final section of the Methods. We note that the method used here—parameterizing GREET-cst with county-specific maize production data—improves on previous related work in which a single run of GREET-cst, which used US national average maize production parameters, was used to estimate maize production air quality damages in the study of maize ethanol and other transportation fuels[33].

County-level agricultural data. County-level agricultural data for 2010–2014 were compiled from publicly available sources. Maize yield ($t\,ha^{-1}\,yr^{-1}$) and production data ($t\,county^{-1}\,yr^{-1}$) were from Quick Stats from the United States Department of Agriculture (USDA) National Agricultural Statistics Service[15], and acreage data ($ha\,county^{-1}\,yr^{-1}$) were from the USDA Farm Service Agency[37].

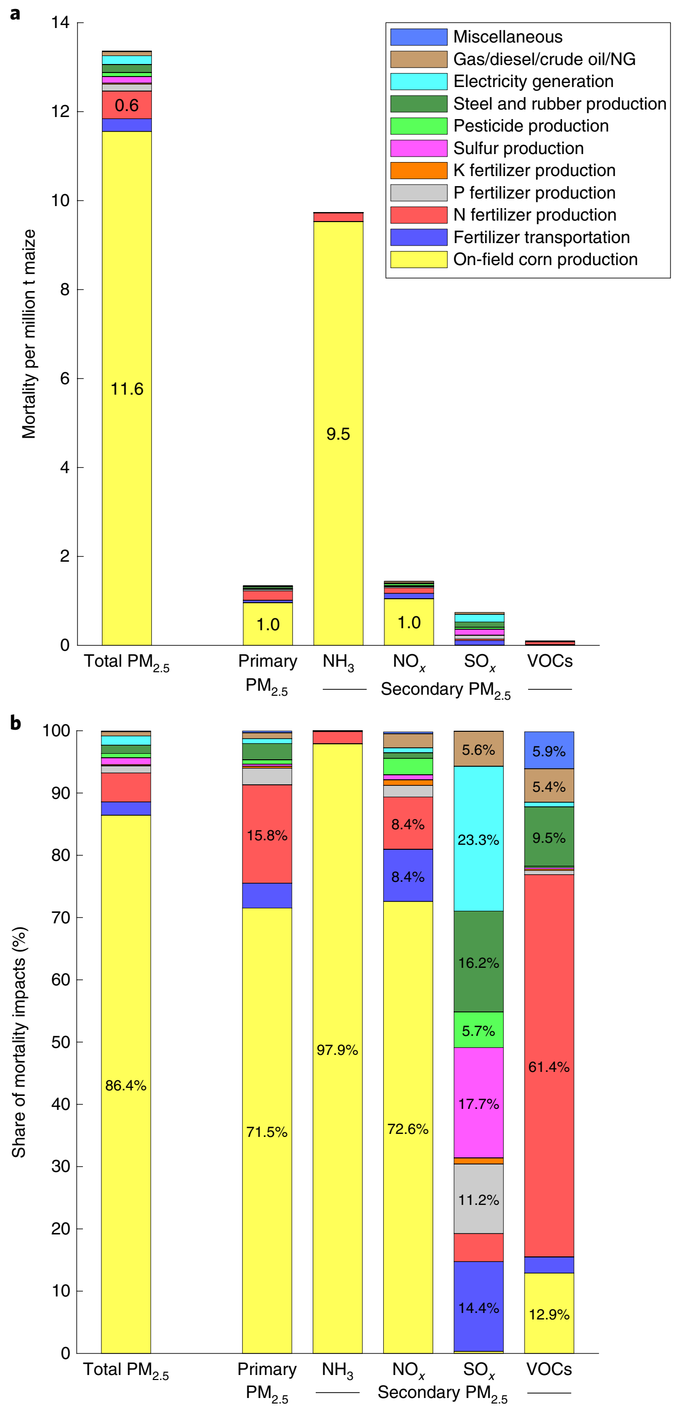

Fig. 5 | Production-weighted national average human mortality per million tonnes of maize produced, by pollutant and supply chain stage. **a**, Absolute mortality. The average annual mortality per million tonnes of maize is 13.4. **b**, Relative mortality. NG, natural gas.

Maize-specific synthetic fertilizer rates (kg ha^{-1} yr^{-1}) and fertilized acreage data (%) were from the USDA Economic Research Service[17]. Fertilizer type data were from the NEI[18]. Manured maize crop acreage (ha state^{-1} yr^{-1}) and application rates (kg ha^{-1} yr^{-1}) were from the Economic Research Service Agricultural Resource Management Survey Farm Financial and Crop Production Practices[38,39]. Maize pesticide application rates (kg ha^{-1} yr^{-1}) and types (acetochlor, atrazine, glyphosate and metolachlor/*S*-metolachlor) were from 2010 and 2014 National Agricultural Statistics Service surveys[15]. For all data, where county-level data were missing, state-level data were used. Where state-level data were missing, national-level data were used.

Emissions. County-specific emissions of NH_3 per tonne of maize (kgNH_3 t^{-1} (maize produced)) were estimated from county-level annual maize yields[15] (t ha^{-1} yr^{-1}) and areal emissions of NH_3 (kg ha^{-1} yr^{-1}) for synthetic fertilizers or manure. Areal emissions of NH_3 from synthetic fertilizers were derived from fertilizer type- and location-specific NH_3 emissions factors (kg NH_3 emitted per kg fertilizer applied) from the Carnegie Mellon University Ammonia Model[40] using fertilizer rates and types as noted above. The average production-weighted emissions factors for maize used in this study were: anhydrous ammonia (4.0%), ammonium nitrate (1.8%), ammonium sulfate (7.7%), diammonium phosphate (5.0%), miscellaneous (4.0%), monoammonium phosphate (5.0%), urea ammonium nitrate solutions (8.0%) and urea (16.3%). Areal emissions of NH_3 from manure were derived from manure rates and acreage, as noted above, using state-specific emissions factors[18] with an average production-weighted emissions factor of 1.15 kgNH_3 t manure applied^{-1}. Emissions from manure, which is both a waste product of animal production and a fertilizer input in maize production, were allocated such that only emissions from manure application were attributed to maize production; emissions from manure handling, storage and confinement were attributed to animal production and thus excluded from this analysis. Over the 2,000 counties included in this analysis, 70% of NH_3 emissions were from synthetic fertilizers, while 30% were from manure.

County-specific emissions of fugitive dust from agricultural activities per tonne of maize were derived from emissions factors of harvest and non-harvest activities (for example, ploughing, planting and pesticide application) for conventional and conservation tillage practices[35]. As in previous work, the resulting emissions factors were scaled down by county-level factors for near-source removal of dust emissions by land cover[34]. These emissions factors were weighted by regional implementation of these practices[36] to obtain regionally specific emissions factors. Over the 2,000 counties included in this analysis, average emissions of primary $PM_{2.5}$ were 1.60 kg ha^{-1} for non-harvest activities and 0.54 kg ha^{-1} for harvest activities. Emissions of GHGs resulting from changes in cultivation practices or land use[41,42] were excluded from this analysis.

Upstream emissions data. Emissions from the domestic production of fertilizer, and from fertilizer imported from Canada and Mexico, were included as described in the NEI[18]. Emissions from fertilizer transport were allocated along county routes from fertilizer production facilities to maize production counties using NEI emissions factors and shapefiles. Emissions of other NH_3-emitting processes were estimated and spatially allocated using NEI Source Classification Codes.

Air quality modelling and impact assessment. We employed the Intervention Model for Air Pollution (InMAP)[12] to conduct reactive dispersion air quality modelling and to estimate the premature mortality in the United States attributable to maize production. InMAP creates spatially explicit estimates of the effect of emissions of primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursors (VOCs, NO_x, NH_3 and SO_x) on atmospheric concentrations of $PM_{2.5}$, the exposure of populations[43,44] to $PM_{2.5}$, and the resulting health[45] and economic[14] effects. InMAP uses a variable spatial resolution from 1 km in urban areas to 48 km in rural areas. We used the concentration-response estimates from a major epidemiological cohort study that inferred the health effects of $PM_{2.5}$ from the average annual outdoor $PM_{2.5}$ concentrations at the place of residence of study participants in the United States[45]. InMAP's structure and evaluation of its performance—including weather inputs and transport–fate–exposure modelling—are described and discussed elsewhere[12,46–49]. The resulting estimates of premature mortality were monetized using a mean estimate of VSL of US\$9.1 million (2017\$), with a range of one standard deviation (US\$5.8 million) above or below[14]. Estimates of climate change damages were monetized using the mean estimate of the SCC, US\$43 t^{-1} of CO_2e (2017\$; 3% discount rate), with a range of US\$13 (5% discount rate) to US\$67 (2.5% discount rate)[16].

Data availability

Data supporting the findings of this study beyond those found in the Supplementary Information are available from the corresponding author upon reasonable request.

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References

1. Smith, P. et al. in *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. et al.) 812–922 (Cambridge Univ. Press, 2014).
2. Tilman, D. et al. Forecasting agriculturally driven global environmental change. *Science* **292**, 281–284 (2001).
3. Lelieveld, J., Evans, J., Fnais, M., Giannadaki, D. & Pozzer, A. The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature* **525**, 367–371 (2015).
4. Bauer, S., Tsigaridis, K. & Miller, R. Significant atmospheric aerosol pollution caused by world food cultivation. *Geophys. Res. Lett.* **43**, 5394–5400 (2016).

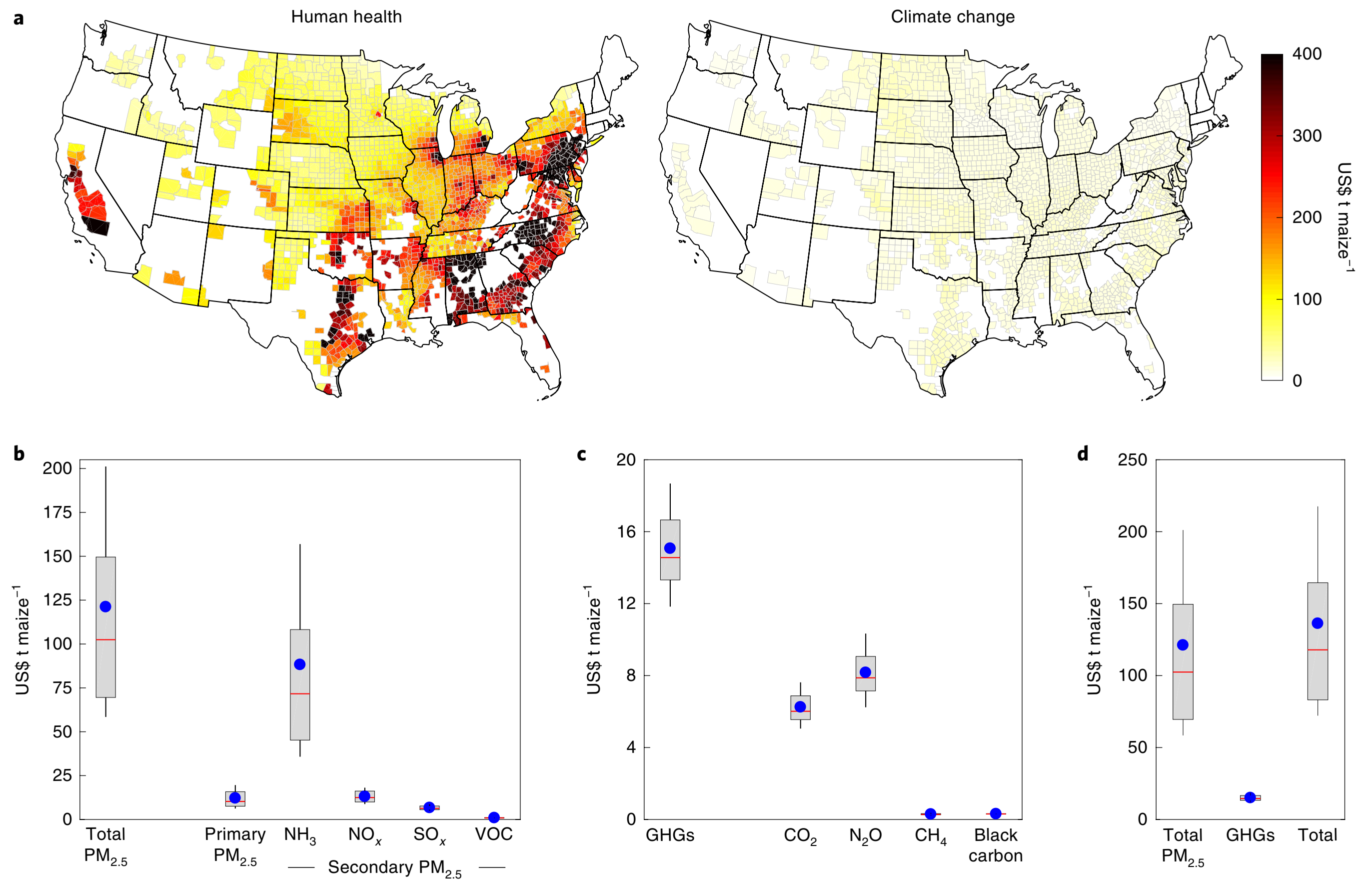

Fig. 6 | County-level per-tonne monetized damages as a result of US maize production at a VSL of US\$9.1 million (2017\$) and GHGs at a SCC of US\$43 (2017\$) per tonne of CO_2e. a, Human health (left) and climate change damages (right) per tonne of maize produced. **b**, County-level per-tonne monetized human health damages from primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursors (NH_3, NO_x, SO_x and VOCs). **c**, County-level per-tonne monetized climate change damages from GHGs (CO_2e). **d**, County-level per-tonne monetized human health and climate change damages. Box plots display 10th, 25th, 50th, 75th and 90th percentiles. Blue dots represent means of the county-level variability across the United States. Box plots show variability among counties, not estimates at different values of VSL and SCC.

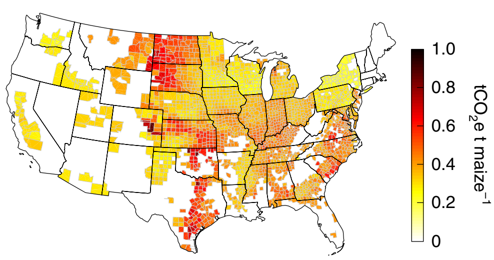

Fig. 7 | GHG emissions per tonne of maize produced. Emissions include on-farm and supporting supply chain activities, attributed here to the county of production. GHG emissions are in CO_2e GWP100. GWP, Global Warming Potential over a 100-year time horizon.

5. Tilman, D., Balzer, C., Hill, J. & Befort, B. Global food demand and the sustainable intensification of agriculture. *Proc. Natl Acad. Sci. USA* **108**, 20260–20264 (2011).
6. Foley, J. et al. Solutions for a cultivated planet. *Nature* **478**, 337–342 (2011).
7. Pope, C. A. & Dockery, D. Health effects of fine particulate pollution: lines that connect. *J. Air Waste Manag. Assoc.* **56**, 709–742 (2006).
8. GBD 2015 Risk Factors Collaborators. Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990–2015: a systematic analysis for the Global Burden of Disease Study 2015. *Lancet* **388**, 1659–1724 (2016).
9. Graff Zivin, J. & Neidell, M. Air pollution's hidden impacts. *Science* **359**, 39–40 (2018).
10. Tessum, C., Marshall, J. & Hill, J. A spatially and temporally explicit life cycle inventory for gasoline and ethanol in the United States. *Environ. Sci. Technol.* **46**, 11408–11417 (2012).
11. Smith, T. et al. Subnational mobility and consumption-based environmental accounting of US corn in animal protein and ethanol supply chains. *Proc. Natl Acad. Sci. USA* **114**, E7891–E7899 (2017).
12. Tessum, C., Hill, J. & Marshall, J. InMAP: a model for air pollution interventions. *PLoS ONE* **12**, 0176131 (2017).
13. Green, T., Kipka, H., David, O. & McMaster, G. Where is the USA Corn Belt, and how is it changing? *Sci. Total Environ.* **618**, 1613–1618 (2018).
14. *Guidelines for Preparing Economic Analyses* (US Environmental Protection Agency, 2014); https://www.epa.gov/sites/production/files/2017-08/documents/ee-0568-50.pdf
15. *Quick Stats* (US Department of Agriculture, 2018); https://quickstats.nass.usda.gov
16. *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, 2016); https://www.epa.gov/sites/production/files/2016-12/documents/sc_co2_tsd_august_2016.pdf
17. *Fertilizer Use and Price* (US Department of Agriculture, 2018); https://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx
18. *2014 National Emissions Inventory (NEI) Data* (US Environmental Protection Agency, 2017); https://www.epa.gov/air-emissions-inventories/2014-national-emissions-inventory-nei-data
19. Pan, B., Kee Lam, S., Mosier, A., Luo, Y. & Chen, D. Ammonia volatilization from synthetic fertilizers and its mitigation strategies: a global synthesis. *Agric. Ecosyst. Environ.* **232**, 283–289 (2016).

20. Pinder, R., Adams, P. & Pandis, S. Ammonia emission controls as a cost-effective strategy for reducing atmospheric particulate matter in the Eastern United States. *Environ. Sci. Technol.* **41**, 380–386 (2007).
21. *World of Corn 2018* (National Corn Growers Association, 2018); http://www.worldofcorn.com/pdf/NCGA_WOC2018_Metric.pdf
22. Hill, J. et al. Climate change and health costs of air emissions from biofuels and gasoline. *Proc. Natl Acad. Sci. USA* **106**, 2077–2082 (2009).
23. Springmann, M., Godfray, H. C., Rayner, M. & Scarborough, P. Analysis and valuation of the health and climate change cobenefits of dietary change. *Proc. Natl Acad. Sci. USA* **113**, 4146–4151 (2016).
24. Springmann, M. et al. Mitigation potential and global health impacts from emissions pricing of food commodities. *Nat. Clim. Change* **7**, 69–74 (2017).
25. Poore, J. & Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science* **360**, 987–992 (2018).
26. Tilman, D. & Clark, M. Global diets link environmental sustainability and human health. *Nature* **515**, 518–522 (2014).
27. *GBD Results Tool* (Univ. Washington Institute for Health Metrics and Evaluation, 2017); http://ghdx.healthdata.org/gbd-results-tool
28. Brandt, J. et al. Contribution from the ten major emission sectors in Europe and Denmark to the health-cost externalities of air pollution using the EVA model system—an integrated modelling approach. *Atmos. Chem. Phys.* **13**, 7725–7746 (2013).
29. Paulot, F. & Jacob, D. Hidden cost of U.S. agricultural exports: particulate matter from ammonia emissions. *Environ. Sci. Technol.* **48**, 903–908 (2013).
30. Giannadaki, D., Giannakis, E., Pozzer, A. & Lelieveld, J. Estimating health and economic benefits of reductions in air pollution from agriculture. *Sci. Total Environ.* **622–623**, 1304–1316 (2018).
31. *GREET Model* (Argonne National Laboratory, 2018); https://greet.es.anl.gov
32. Tessum, C., Hill, J. & Marshall, J. spatialmodel/inmap: v1.5.1 *Zenodo* https://zenodo.org/record/2549859 (2018).
33. Tessum, C., Hill, J. & Marshall, J. Life cycle air quality impacts of conventional and alternative light-duty transportation in the United States. *Proc. Natl Acad. Sci. USA* **111**, 18490–18495 (2014).
34. Thakrar, S., Goodkind, A., Tessum, C., Marshall, J. & Hill, J. Life cycle air quality impacts on human health from potential switchgrass production in the United States. *Biomass Bioener.* **114**, 73–82 (2018).
35. Zhang, Y., Heath, G., Carpenter, A. & Fisher, N. Air pollutant emissions inventory of large-scale production of selected biofuels feedstocks in 2022. *Biofuel. Bioprod. Bior.* **10**, 56–69 (2016).
36. Wade, T., Claassen, R. & Wallander, S. *Conservation-Practice Adoption Rates Vary Widely by Crop and Region* (Economic Information Bulletin No. 147, US Department of Agriculture, 2015).
37. *Crop Acreage Data* (US Department of Agriculture, Farm Service Agency, 2018); https://www.fsa.usda.gov/news-room/efoia/electronic-reading-room/frequently-requested-information/crop-acreage-data/index
38. *ARMS Data:Economic Research Service (ERS) Agricultural Resource Management Survey (ARMS) Tailored Reports* (US Department of Agriculture, Economic Research Service, 2018); https://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/arms-data/
39. MacDonald, J., Ribaudo, M., Livingston, M., Beckman, J. & Huang, W. *Manure Use for Fertilizer and for Energy* (2009); https://naldc.nal.usda.gov/download/46168/PDF
40. Davidson, C. et al. *CMU Ammonia Model v3.6* (The Environmental Institute, Carnegie Mellon Univ., 2004).
41. Lark, T., Salmon, J. & Gibbs, H. Cropland expansion outpaces agricultural and biofuels policies in the United States. *Environ. Res. Lett.* **10**, 044003 (2015).
42. Lu, C. et al. Increasing carbon footprint of grain crop production in the US Western Corn Belt. *Environ. Res. Lett.* **13**, 124007 (2018).
43. Manson, S., Schroeder, J., Van Riper, D. & Ruggles, S. *IPUMS NHGIS: version 12.0* (Univ. Minnesota, 2017); https://doi.org/10.18128/D050.V12.0
44. *American FactFinder* (US Census Bureau, 2018); https://factfinder.census.gov/faces/nav/jsf/pages/index.xhtml
45. Krewski, D. et al. *Extended Follow-up and Spatial Analysis of the American Cancer Society Study Linking Particulate Air Pollution and Mortality* Report 140 (Health Effects Institute, 2009); https://www.healtheffects.org/system/files/Krewski140.pdf
46. Paolella, D. et al. Effect of model spatial resolution on estimates of fine particulate matter exposure and exposure disparities in the United States. *Environ. Sci. Technol. Lett.* **5**, 436–441 (2018).
47. Tessum, C., Hill, J. & Marshall, J. Twelve-month, 12 km resolution North American WRF-Chem v3.4 air quality simulation: performance evaluation. *Geosci. Model Dev.* **8**, 957–973 (2015).
48. Tessum, C., Hill, J. & Marshall, J. InMAP: Intervention Model for Air Pollution: health impacts of air pollution: a tool to understand the consequences. *InMAP* http://spatialmodel.com/inmap/ (2018).
49. Tessum, C., Hill, J. & Marshall, J. Evaluation data for the Intervention Model for Air Pollution (InMAP) version 1.3. *Zenodo* https://zenodo.org/record/848824 (2017).

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Author contributions

J.H. and A.G. conceived and designed the experiments. J.H., A.G. and C.T. performed the experiments. J.H., A.G., C.T. and D.T. analysed the data. J.H., A.G., C.T., S.T., N.H. and K.M. contributed materials/analysis tools. All authors wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

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