AIR POLLUTION

Abating ammonia is more cost-effective than nitrogen oxides for mitigating $PM_{2.5}$ air pollution

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Fine particulate matter ($PM_{2.5}$, particles with a mass median aerodynamic diameter of less than 2.5 micrometers) in the atmosphere is associated with severe negative impacts on human health, and the gases sulfur dioxide, nitrogen oxides, and ammonia are the main $PM_{2.5}$ precursors. However, their contribution to global health impacts has not yet been analyzed. Here, we show that nitrogen accounted for 39% of global $PM_{2.5}$ exposure in 2013, increasing from 30% in 1990 with rising reactive nitrogen emissions and successful controls on sulfur dioxide. Nitrogen emissions to air caused an estimated 23.3 million years of life lost in 2013, corresponding to an annual welfare loss of 420 billion United States dollars for premature death. The marginal abatement cost of ammonia emission is only 10% that of nitrogen oxides emission globally, highlighting the priority for ammonia reduction.

Air pollution from $PM_{2.5}$ (fine particulate matter with a mass median aerodynamic diameter <2.5 μm) has been estimated to cause millions of premature deaths annually in recent years (*1*, *2*). Therefore, mitigating $PM_{2.5}$ pollution is a high priority for environmental protection in many countries such as China (*3*), India (*4*), the United States (*5*), and the member states of the European Union (EU) (*6*). The most cost-effective abatement measures need to be identified to balance environmental protection and economic development. This is particularly relevant for atmospheric emissions of reactive nitrogen (N_r), which are generally driven by fossil fuel combustion in power plants and transport and by the production of food and energy (*7*–*9*). Previous quantifications of the health impacts of nitrogen oxides (NO_x) and ammonia (NH_3) emissions from $PM_{2.5}$ pollution have not been conducted on a global scale because of differences in atmospheric chemistry, population density, and exposure characteristics relative to the pollution consequences of N_r emissions in different countries (*7*, *9*–*11*). In addition, differences in gross domestic product (GDP) and social preferences affect economic values of mortality (*1*). Economic growth and higher living standards increase healthy life expectancy and also increase the willingness to pay for actions that ultimately reduce the health risks of air pollution (*1*). Thus, a generic method is needed to ensure that the costs of mortality from N_r emissions are comparable across countries and regions and reflective of local conditions.

Here, we developed and applied a metric that we call the "N-share" of $PM_{2.5}$ pollution, which is the contribution of N_r compounds to total $PM_{2.5}$ concentration determined by modeling with and without N_r emission. We applied three atmospheric chemistry transport models, EMEP-WRF (*12*), TM5-FASST (*13*), and GEOS-Chem (*14*), which include emissions of sulfur dioxide (SO_2), NO_x, NH_3, volatile organic compounds, and primary $PM_{2.5}$ (see the materials and methods). The N-share is different from the mass fraction of N_r within $PM_{2.5}$ because N_r emissions are not only the precursors of $PM_{2.5}$ but also affect the chemical reactions that lead to $PM_{2.5}$ formation (*15*). By combining the calculated values of N-share with the estimated global burden of disease derived from $PM_{2.5}$ pollution (*1*), we were able to estimate welfare loss associated with N_r emissions. Finally, we applied the GAINS model (*16*) to estimate the implementation costs of N_r air pollution abatement (see the materials and methods), which has the advantage of being able to quantify the abatement cost of each measure in different countries, allowing us to compare the relative welfare gains of reducing different forms of N_r emission. NO_x is an important precursor to ozone that also has a negative impact on human health (*9*), so we also considered ozone formation in the analysis. By contrast, we have not separately analyzed the direct health impacts of NO_2.

Although the overall N-share of $PM_{2.5}$ pollution generally increased from 1990 to 2013, we note substantial regional variation, with increases in Asia, South America, and South Africa and a decrease in Europe (Fig. 1 and Table 1). We found that NH_3 emission made a larger contribution to $PM_{2.5}$ than NO_x emission globally and in most countries, indicating that $PM_{2.5}$ is more strongly NH_3 limited than NO_x limited (*17*, *18*). The N-share caused by NH_3 emissions contributed an estimated 25% (range, 20 to 31%) to $PM_{2.5}$ pollution in 1990, increasing to 32% (25 to 39%) in 2013, whereas NO_x emission contributed 17% (14 to 20%) in 1990, increasing to 28% (23 to 33%) in 2013. These changes agree well with the widespread increase of N_r emissions and the decrease of SO_2 emission in many areas of the world from 1990 to 2013 (fig. S5) (*19*).

The N-shares of total N_r emissions are much smaller than the sum of N-shares from NH_3 and NO_x separately (Fig. 1) because of the interactions between NH_3 and NO_x during secondary $PM_{2.5}$ formation. Alkaline NH_3 can form aerosols with the acidic products of NO_x and SO_2 emission, so that reduction of NH_3 emission also tends to reduce the contribution of NO_x and SO_2 to $PM_{2.5}$ formation (*15*, *18*, *20*), which also explains the larger N-share of $PM_{2.5}$ pollution arising from NH_3 compared with NO_x. In this study, we treated the health effects of NH_3-derived $PM_{2.5}$ the same as we did those of NO_x-derived $PM_{2.5}$ because evidence of differential harm between chemical species is lacking (see the supplementary materials) (*21*).

For the period 1990–2013, we estimate that total years of life lost (YLL) caused by $PM_{2.5}$ pollution derived from N_r emissions increased from 19.5 to 23.3 million globally, with the NH_3 and NO_x contributions increasing from 16.3 to 19.3 and 11.4 to 16.2 million, respectively (table S1 and fig. S6). We used YLL to quantify premature mortality because this metric is considered robust and versatile in capturing health impacts (*22*). Every premature death represents an individual story, with variation between age at death and expected lifespan, which can be well captured by the YLL (*23*). When expressed as YLL per gigogram of N (where 1 Gg = 10^9 g) emission (YLL/N), higher values were found in developing or transition economies such as Asia, East Europe, and some African countries, which have high $PM_{2.5}$ pollution and lower GDP per capita (Fig. 2 and fig. S6). Higher $PM_{2.5}$ pollution increases the YLL, whereas lower GDP per capita normally indicates lower access to and quality of medical care (table S2) (*24*), as well as greater insecurity in access to food and water that can also increase the YLL/N. By contrast, lower YLL/N is found in

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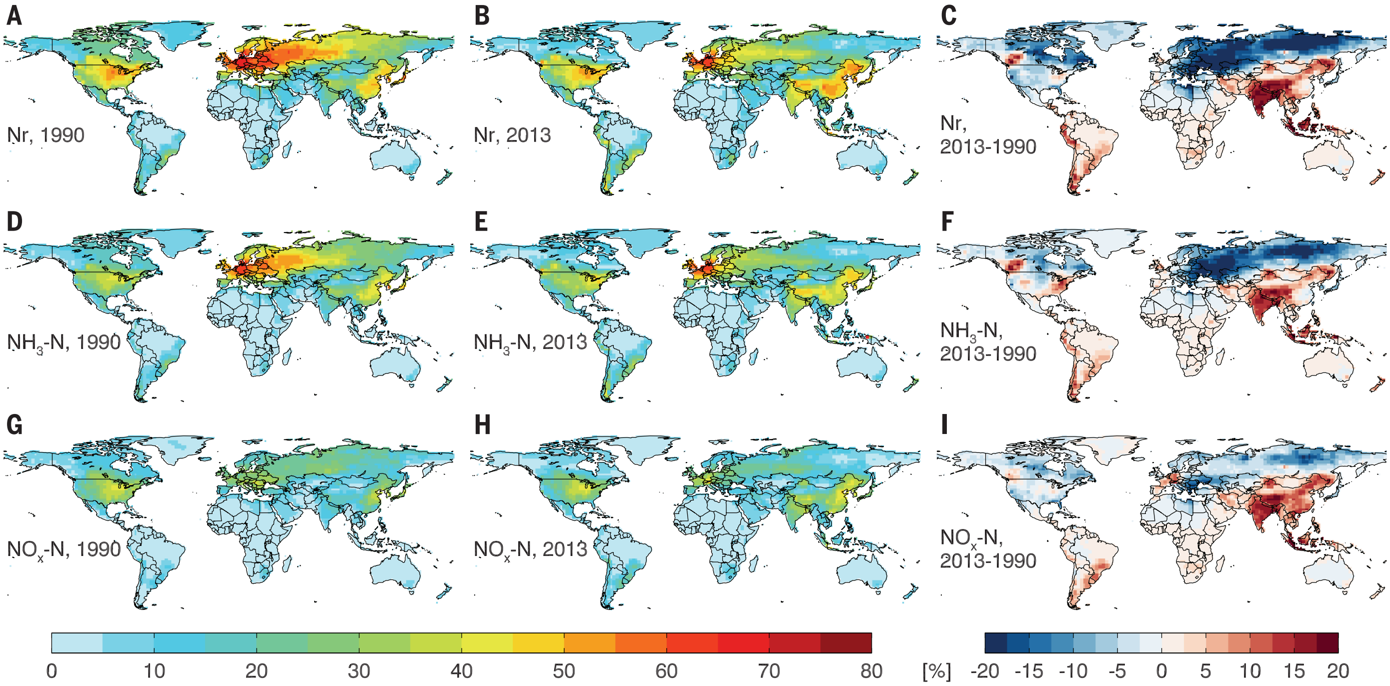

Fig. 1. N-shares of $PM_{2.5}$ pollution and their changes between 1990 and 2013. Values represent the percentage contribution of each form of N_r emission to $PM_{2.5}$ pollution. (**A**) Total N_r-share in 1990. (**B**) Total N_r-share in 2013. (**C**) Change in total N_r-share between 2013 and 1990. (**D**) NH_3-N share in 1990. (**E**) NH_3-N share in 2013. (**F**) Change in NH_3-N share between 2013 and 1990. (**G**) NO_x-N share in 1990. (**H**) NO_x-N share in 2013. (**I**) Change in NO_x-N share between 2013 and 1990. (**J**) Change in NO_x-N share between 2013 and 1990. Results are based on the average value of simulations from GEOS-Chem and EMEP-WRF models using 100% N_r emission reduction with uncertainty analysis from figs. S2 to S5. Base map is applied without endorsement from Natural Earth (https://www.naturalearthdata.com/).

Table 1. Estimated mortality cost caused by $PM_{2.5}$ air pollution from total N_r emissions

	N_r shares in $PM_{2.5}$ formation (%)		YLL attributable to $PM_{2.5}$ from N_r emission (million years)		Total mortality cost of N_r in $PM_{2.5}$ pollution (billion USD)		Marginal mortality cost (USD/kg N)	
	1990	2013	1990	2013	1990	2013	1990	2013
Africa	5.9	7.3	0.9	0.9	6.3	9.3	1.3	1.1
Asia	31.0	42.3	13.4	18.1	49.4	212.4	1.6	4.1
Europe	57.9	47.4	3.8	2.9	148.6	124.6	8.4	13.1
Latin America	20.9	23.5	0.6	0.7	8.6	19.0	1.5	2.1
North America	46.3	44.2	0.8	0.8	47.6	53.6	4.3	6.8
Oceania	7.8	11.2	0.01	0.01	0.5	0.6	0.6	0.5
World	30.2	38.6	19.5	23.3	261.1	419.5	3.6	4.8

America, western Europe, and Oceania (fig. S6). In these areas, populations are generally exposed to lower levels of $PM_{2.5}$ pollution compared with Asia, and higher GDP per capita is associated with access to better medical care (table S2).

Quantifying the global welfare loss per YLL [in 2011 U.S. dollars (USD) converted at purchasing power parity rates], we found that the willingness to pay to reduce the risk of a YLL caused by N_r emission represented a total cost of 261 (range, 156 to 398) billion USD in 1990, increasing by 60% to 420 (247 to 640) billion USD in 2013 (Table 1). Of this, by far the largest regional change was estimated for Asia (+330%, mainly linked to increased N_r emissions), which may be contrasted with reduction in Europe (–16%, mainly linked to NO_x control). Ammonia contributes most to the estimated total cost of mortality from N_r emissions both because it is found in large amounts (table S1) and because it is the limiting (alkaline) compound for aerosol formation (*17*, *18*).

Globally, the average marginal cost of premature mortality caused by N_r emission in 2013 was estimated at 4.8 (range, 2.8 to 7.3) USD/kg N_r emission, compared with 3.6 (2.2 to 5.5) USD/kg N_r emission in 1990 (Table 1, Fig. 2, and fig. S7). This 31% increase can be mainly attributed to increase of N_r air pollution and higher costs per YLL caused by income growth. The marginal cost from NH_3 emission was ~44% higher than that of total N_r emission (table S1), affecting the overall pattern of N_r values (Fig. 2).

We found that the total social benefit of reduced mortality from the abatement of NH_3 emission was substantially larger than the

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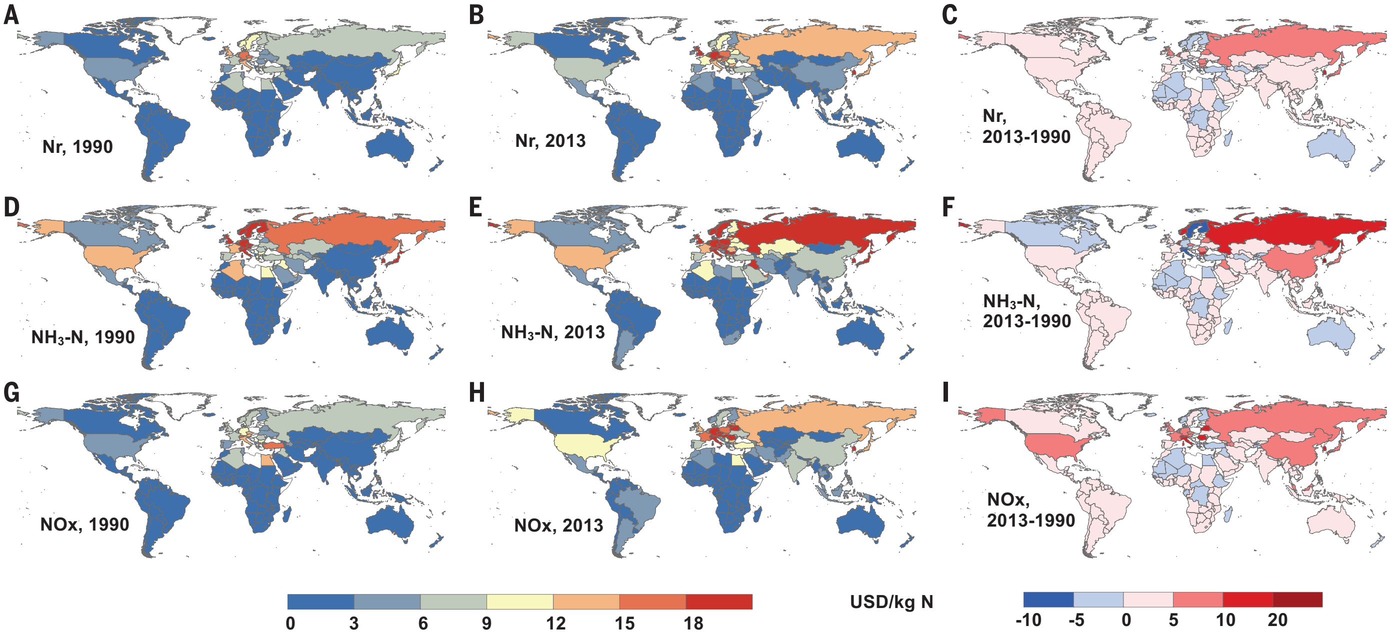

Fig. 2. Changes in mortality cost per kilogram N_r emission between 1990 and 2013 caused by $PM_{2.5}$ pollution. Values are based on the control of different N_r components. Shown are control of total N_r emission for 1990 (**A**), 2013 (**B**), and differences between 2013 and 1990 (**C**); control of NH_3 emission for 1990 (**D**), 2013 (**E**), and differences between 2013 and 1990 (**F**); and control of NO_x emission for 1990 (**G**), 2013 (**H**), and differences between 2013 and 1990 (**I**). Positive values for (C), (F), and (I) indicate an increase over time. Uncertainties for these figures can be found in fig. S7. White areas of some countries indicate a lack of data. Base map is applied without endorsement from Natural Earth (https://www.naturalearthdata.com/).

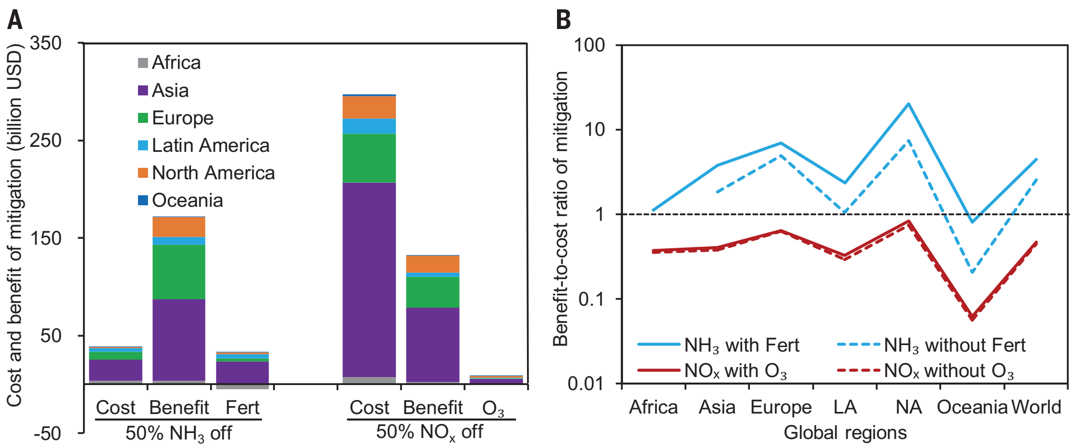

Fig. 3. Cost and benefit to reduce 50% of NH_3 and NO_x emission in 2013. (**A**) Abatement cost, benefit of prevented mortality from reduced $PM_{2.5}$, fertilizer saving (Fert), and ground-level ozone pollution (O_3) mitigation. (**B**) Ratio of benefit of prevented mortality from $PM_{2.5}$ mitigation to cost, with values for NH_3 and NO_x shown with and without the benefit from fertilizer saving and O_3 mitigation caused by NO_x reduction, respectively. The benefit in (B) only refers to benefit of prevented mortality derived from $PM_{2.5}$ mitigation caused by NH_3 and NO_x abatement. LA, Latin America, NA, North America. For Africa, fertilizer savings are negative because of too little N_r input compared with crop need, and the best management practices would increase N_r fertilizer use (see the supplementary materials).

abatement costs. We estimated the global average cost of reducing NH_3 emission at 1.5 USD/kg NH_3-N (weighted mean of measures) using the GAINS method (see the materials and methods), which is substantially less than the welfare benefit of the associated reduction of mortality at 6.9 (range, 3.8 to 10.9) USD/kg NH_3-N globally (Table 1 and fig. S8). By contrast, we estimated the abatement cost of NO_x emission at 16.0 USD/kg NO_x-N, which is larger than the welfare benefits of reduced mortality at 7.3 (4.0 to 11.8) USD/kg NO_x-N (table S1).

North America has the largest benefit-to-cost ratio for NH_3 mitigation, followed by Europe and Asia, suggesting reduction of NH_3 emission as a favorable option to increase social benefit (Fig. 3B). The benefit-to-cost ratio for NO_x mitigation is also the largest in North America compared with other world regions. However, globally, this ratio is <1 even when including both $PM_{2.5}$ and ozone effects, suggesting a negative net benefit to further reducing NO_x emissions (Fig. 3B). The benefit-to-cost ratios to mitigate NH_3 and NO_x emission are both <1 in Oceania (Fig. 3B). This indicates that the costs of N_r mitigation are not justified by the expected regional benefits for $PM_{2.5}$, although other considerations may still justify N_r mitigation in this region [e.g., ecosystem benefits (*25*)]. In Africa, food security is still a challenge, and improved management practices may need to increase nitrogen inputs (whether

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by fertilizer or biological nitrogen fixation) and reduce wasteful nitrogen losses to avoid soil degradation (*26*).

The main opportunities for NH_3 abatement concern agricultural sources, for which abatement measures are relatively easy and inexpensive. For instance, optimizing nitrogen fertilization will not only abate NH_3 emission but will also reduce nitrogen fertilizer use, which can save the implementation cost while offering opportunities for net cost savings (*27*–*29*). For nonagricultural sources of NH_3, which account for ~25% of emissions based on the Community Emissions Data System (CEDS) inventory, the reduction is more related to fossil fuel combustion, biomass burning, and waste treatment, which have received much less attention in the past (*30*). If global NH_3 emissions (from all sources, including both agricultural and nonagricultural) were to be reduced by 50%, then the total implementation cost is estimated at 38 billion USD (Fig. 3A). This is smaller than the social benefit of prevented mortality (172 billion USD) derived from mitigation of $PM_{2.5}$ pollution for NH_3 emission (Fig. 3A). Additionally, this would save ~20% of global nitrogen fertilizer use with a net value of ~28 billion USD (see the materials and methods for the calculation). In practice, this means that many measures to control NH_3 emission can have a zero cost implementation or represent a net economic benefit for farmers. This is in addition to the substantial societal co-benefits for natural ecosystems from reducing N_r air pollution (*8*, *31*, *32*), such as improved water quality, biodiversity conservation, and reduced nitrous oxide emissions (*33*).

Agricultural NH_3 is distributed over many individual facilities, so control requires action by farmers in many different contexts (*34*). In the United States, agricultural NH_3 emission is not well controlled, and it is a cause of damage to both the environment and human health (*18*). For larger farms with access to advanced technologies, it is technically feasible to reduce NH_3 emission from agriculture without risk of production loss through measures such as adoption of enhanced-efficiency fertilizers and improved manure management practices (*35*, *36*). With the revised EU National Emission Ceilings directive (adopted in 2016), reduction of NH_3 emission will be considered across sectors for the target year 2030 (*37*). Policies in the Netherlands and Denmark have required NH_3 abatement, leading to reported emission reductions of 35 to 66% between 1990 and 2011 (*38*). China started to address reduction of NH_3 emission from agricultural sources during its 13th Five Year Plan (2016–2020) (*39*), and it has been estimated that agricultural NH_3 emission could be reduced by one-third and at a low cost through appropriate policies, such as subsidies for enhanced-efficiency fertilizers and fertilizer application machinery (*40*, *41*). Taking reduction of NH_3 emission into consideration for $PM_{2.5}$ pollution control is therefore critical, presenting the opportunity for future legislation to mitigate NH_3 emissions at national to global scales (*34*).

The estimated implementation cost (297 billion USD) for reducing NO_x emissions is larger than the benefit of reduced mortality (132 billion USD) derived from reduced $PM_{2.5}$ pollution (fig. S8). However, reduction of NO_x emission can also have other benefits, such as alleviation of ground-level ozone (9 billion USD, estimated based on the similar method with $PM_{2.5}$; see the supplementary materials). The modest 7% additional benefit shows how the $PM_{2.5}$ costs dominate welfare loss derived from NO_x emission (Fig. 3B), whereas reducing both NO_x and NH_3 emissions will also benefit terrestrial and aquatic ecosystems (*9*). NO_x emissions have already been reduced in high-income regions such as North America and Europe between 1990 and 2013 (fig. S5), which means that the marginal implementation cost to reduce NO_x emissions further is much higher in these countries because the most cost-effective measures are in place already. For other countries where NO_x emissions are still increasing, implementation costs are smaller than those for Europe and North America, but even these costs are much higher than those of NH_3 mitigation (fig. S8 and Table 1). Innovation to recapture NO_x as value-added N_r products rather than the present focus on wasteful destruction to form di-nitrogen (N_2) may have considerable future potential to reduce costs (*33*) but is still far from commercial availability. Considering the overall costs and benefits, our analysis highlights the priority for air pollution policies to give increased attention to controlling NH_3 emissions, complementing successful policies on NO_x and SO_2 (Fig. 3B) as part of implementing the ambition of the Colombo Declaration to "halve nitrogen waste" from all sources globally.

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29/Z/ST10/02986 (NCN, Poland), 71961137011 (NSFC, China), and 870234 (FFG, Austria). D.C. acknowledges support received from the Australian Research Council through the Industrial Transformation Research Hub (IH200100023). **Author contributions:** B.G. and H.JM.V.G. designed the study as part of the wider INMS framework designed by M.A.S. R.V.D., M.V., and L.Z. applied the global atmospheric models. B.G. conducted the health impact calculation and analysis with help from R.V.D. L.Z. conducted the N-share analysis with help from R.V.D. and M.V. S.Z. and X.Z. conducted the abatement cost analysis using the GAINS model with help from W.W. S.W. and C.R. conducted the spatial and statistical analyses. B.G. analyzed all the data, interpreted the results, and wrote the first draft of the paper. All authors contributed to the discussion and revision of the paper, which was finalized under the lead of B.G. and M.A.S. **Competing interests:** The authors declare no competing interests. **Data and materials availability:** Data supporting the main findings can be found in the supplementary materials. Further data that support the findings of this study are collated from online open databases or literature sources as cited in the reference list.

SUPPLEMENTARY MATERIALS

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Materials and Methods
Supplementary Text
Figs. S1 to S9
Tables S1 to S6
References (*42–64*)

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Little things matter
Particulate air pollution 2.5 micrometers or smaller in size (PM2.5) is a major cause of human mortality, and controlling its production is a health policy priority. Nitrogen oxides are an important precursor of PM2.5 and have been a focus of pollution control programs. However, Gu *et al*. now show that abating ammonia emissions is also an important component of PM2.5 reduction, and the societal benefits of abatement greatly outweigh the costs (see the Perspective by Erisman). Reducing ammonia emissions thus would be a cost-effective complement to nitrogen oxides and sulfur dioxide controls. —HJS

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