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ENVIRONMENTAL STUDIES

Aspirational nitrogen interventions accelerate air pollution abatement and ecosystem protection

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Although reactive nitrogen (Nr) emissions from food and energy production contribute to multi-dimensional environmental damages, integrated management of Nr is still lacking owing to unclear future mitigation potentials and benefits. Here, we find that by 2050, high-ambition compared to low-ambition N interventions reduce global ammonia and nitrogen oxide emissions by 21 and 22 TgN/a, respectively, equivalent to 40 and 52% of their 2015 levels. This would mitigate population-weighted PM2.5 by 6 g/m^3 and avoid premature deaths by 817 k (16%), mitigate ozone by 4 ppbv, avoid premature deaths by 252k (34%) and crop yield losses by 122 million tons (4.3%), and decrease terrestrial ecosystem areas exceeding critical load by 420 Mha (69%). Without nitrogen interventions, most environmental damages examined will deteriorate between 2015 and 2050; Africa and Asia are the most vulnerable but also benefit the most from interventions. Nitrogen interventions support sustainable development goals related to air, health, and ecosystems.

INTRODUCTION

Food and energy production are essential for human well-being but emit reactive nitrogen [N_r; ammonia (NH_3), nitrogen oxides (NO_x), nitrous oxide (N_2O), nitrate (NO_3^-), etc.]. N_r contributes to air and water pollution, biodiversity losses, stratospheric ozone depletion, and climate change (*1*). To address this sustainable development challenge, numerous studies analyzed N_r mitigation opportunities from changing food consumption (*2–4*) and production practices (*5–7*) and clean energy transitions (*8–10*). However, a gap exists between traditional nitrogen budget research and earth system research. The former typically adopts the nitrogen flow approach representing multiple N_r impact pathways at country/region nitrogen flow levels (*3*, *4*, *9*); the latter, instead, conducted geographically varied analyses but for only one specific strategy, region, or impact pathway (*7*, *11–13*). Integrated analyses covering multi-pollutants and multi-impact pathways while reflecting that their spatial variations are lacking (*14*), which are necessary for incentivizing coordinated governance of N_r pollution (*8*, *15*, *16*).

Among socioeconomic damages posed by N_r valued at 70 to 320 billion Euro per annum (/a) in the European Union in 2000, most occurs through adverse human health impacts of N_r-contributed air pollution, followed by terrestrial biodiversity losses from excess N deposition (*8*). NH_3 and NO_x are precursors of secondary inorganic aerosols in $PM_{2.5}$ (fine particulate matter with thermodynamic diameter less than 2.5 μm) (*17*); their anthropogenic emissions have been responsible for 6.4 million premature deaths (39% of all $PM_{2.5}$-related premature deaths) in 2019 (*18*). NO_x also serves as a precursor of tropospheric O_3 pollution, exposure to O_3 led to 0.4 million premature deaths in 2019 (*19*), and 3 to 7% global yield losses (ranges for major crops) (*20*). Excess deposition of N_r [ammonium (NH_4^+) and NO_3^- aerosols, gaseous NH_3, etc.] from the atmosphere into the biosphere has damaged biodiversity in sensitive ecosystems in North America and Europe (*21–23*) through soil acidification, direct toxicity, and deaths of species that have adapted to a N-limited environment (*24–26*).

Despite such complex cascading damages, N_r is currently regulated by singular compound and singular impact in a limited number of countries. Energy-related NO_x emissions have been regulated by clean air legislations, e.g., those in the US (*27*), China (*28*), and Europe (*29*), and will be further indirectly addressed by climate policies that will cut fossil fuel combustion (*15*). NH_3 emissions are regulated in the European Union under National Emission Ceilings for ecosystem conservation (*30–32*), become recently moderately regulated in parts of China for air quality (*33*), but remain largely ignored elsewhere.

To inform policymakers with potentials of N_r interventions in addressing contemporary environmental and health challenges, global future nitrogen policy scenarios and gridded N_r emission projections are critical but have been lacking. As a result, most air quality and ecological management research have focused on general emission abatement strategies or synergies between climate and air pollution management (*34*). Future multisectoral N_r mitigation opportunities, especially those from food, energy, and sewage waste systems and their benefits for future environmental management require in-depth quantifications. Some key nitrogen interventions would include increasing crop system nitrogen use efficiency (NUE), increasing livestock manure recycling rate, reducing food loss and waste, reducing NO_x emissions by modifying combustion conditions, etc. (table S1) (*35*).

Here, we quantify the potentials of aspirational N_r interventions (i.e., technically feasible and achievable if socioeconomic/political barriers could be removed) in addressing future global $PM_{2.5}$ and O_3 air pollution and excess nitrogen deposition, damages of which rank the top two among all N_r impact pathways. Taking advantage of the recently available future scenarios where various levels of nitrogen policy ambitions (low, medium, and high) are imposed upon representative

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socioeconomic development and climate policy settings [i.e., the International Nitrogen Management System (INMS) scenarios (*35*); see Materials and Methods], we constructed our own integrated modeling framework (Fig. 1 and fig. S1) that quantifies consequent N_r (NH_3 and NO_x) emissions; global N_r-related air pollution ($PM_{2.5}$ and O_3) and excess nitrogen deposition; and health impacts for humans (air pollution exposure–induced premature deaths), crops (air pollution exposure-induced yield losses), and ecosystems (excess N deposition–induced risks of biodiversity losses) (Fig. 1 and fig. S1). Substantial synergies between N_r pollution management and multiple environmental and health objectives (clean air and ecosystem biodiversity protection) have been revealed, which may incentivize accelerated progresses toward sustainable development (*15*, *36*, *37*). Effects of climate policies and N_r-specific policies for addressing future $PM_{2.5}$ and O_3 air pollution are evaluated, providing implications for future clean air policymaking. Our spatially refined evaluation of environmental/health benefits of nitrogen interventions and temporal evolvements of N_r-related air and ecosystem impacts may incentivize policymakers to plan locally specific N_r interventions to maximize environmental/health co-benefits while avoiding deteriorated N_r damages.

RESULTS

Future emission reductions achieved through nitrogen interventions

Here, we consider five INMS future scenarios: Three of them have middle-of-the-road conditions for socioeconomic development and climate policy but are accompanied with low-, medium-, and high-ambition N interventions, respectively; the other two scenarios are either highly sustainable or polluting (see tables S2 and S3). Projected anthropogenic NH_3 and NO_x emissions in major world regions in 2015, 2030, and 2050 are illustrated in Fig. 2 (A and B) and fig. S2. Between 2015 and 2050, three INMS scenarios under [shared socioeconomic pathways (SSPs) and representative climate pathways (RCPs)] SSP2-RCP4p5 project −12 to +28% changes in global anthropogenic NH_3 emissions and −60 ~ −2% changes in NO_x emissions (Fig. 2 and fig. S3). NH_3 emissions are expected to grow for all regions under the low-ambition N policy scenario and for Southeast Asia and the former Soviet Union even under medium- or high-ambition N policy scenarios. This is because growing food demand and, thus, production have dominated and outcompeted the mitigation effects of technological advancements. For NO_x, declining

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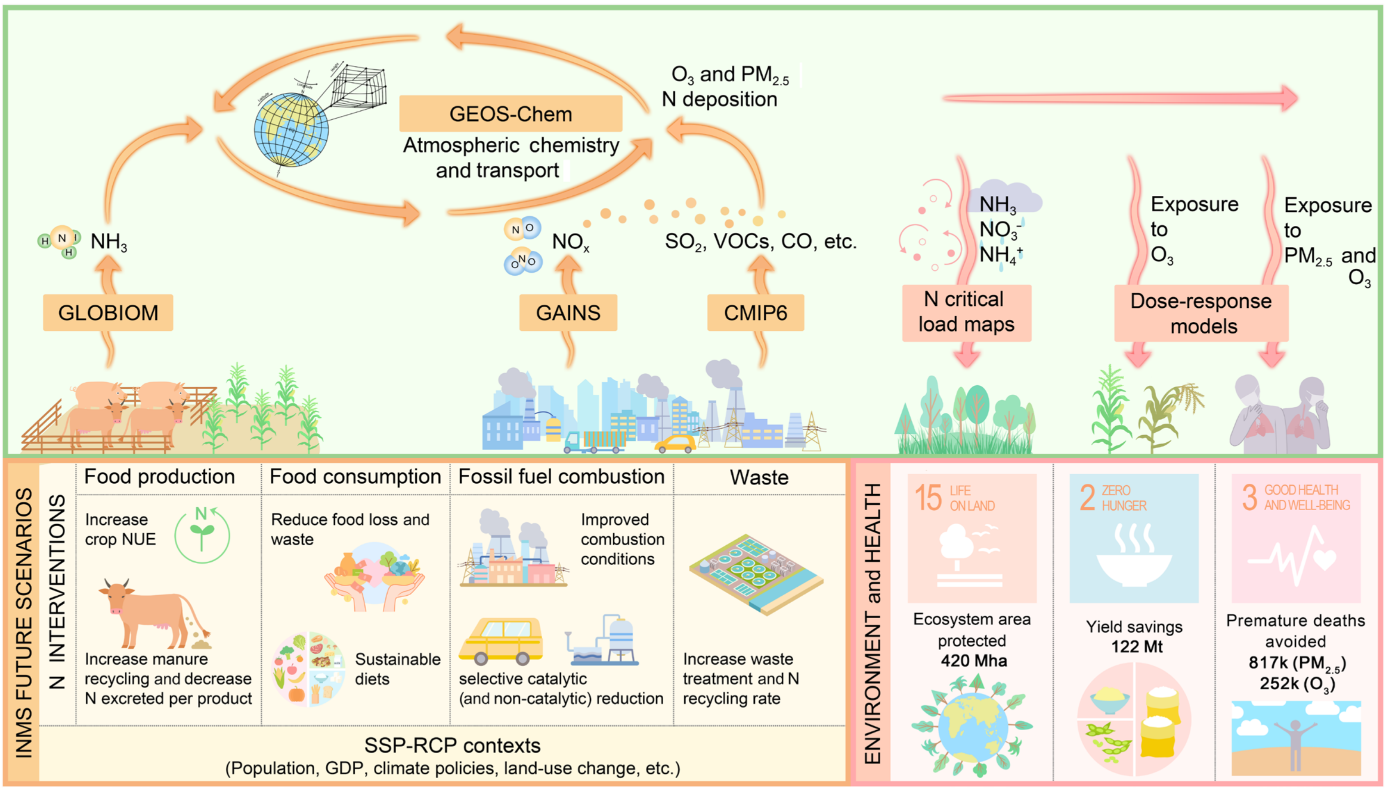

Fig. 1. An integrated modeling framework for assessing potentials of aspirational N interventions in reducing N_r (NH_3 and NO_x) emissions, consequently $PM_{2.5}$, O_3, and N deposition, thus providing benefits for environment and health. Our analyses start with five INMS scenarios (bottom-left block), representing different degrees of nitrogen intervention ambitions targeting food production and consumption, fossil fuel combustion, and waste management within shared socioeconomic development and representative climate policy pathways (SSP-RCPs) contexts and modeling chains for impact assessment (top block; see Materials and Methods and fig. S1) and benefit analyses (bottom-right block). The INMS scenarios, once implemented into the Global Biosphere Management Model (GLOBIOM) (*3*) and Greenhouse Gas and Air Pollution Interactions and Synergies model (GAINS) (see Materials and Methods), project future gridded agricultural NH_3 and anthropogenic NO_x emissions. Combining projections of N_r and non-N_r emissions from the CMIP6 models, we use the state-of-the-art global atmospheric chemistry transport model Goddard Earth Observing System Chemistry (GEOS-Chem) to simulate atmospheric chemistry and transport, as well as O_3 and $PM_{2.5}$ air quality and N deposition. We use critical load maps and dose-response models to quantify ecosystem impacts of excess N deposition, crop yield losses of O_3 exposure, and human health impacts of exposure to O_3 and $PM_{2.5}$ air pollution.

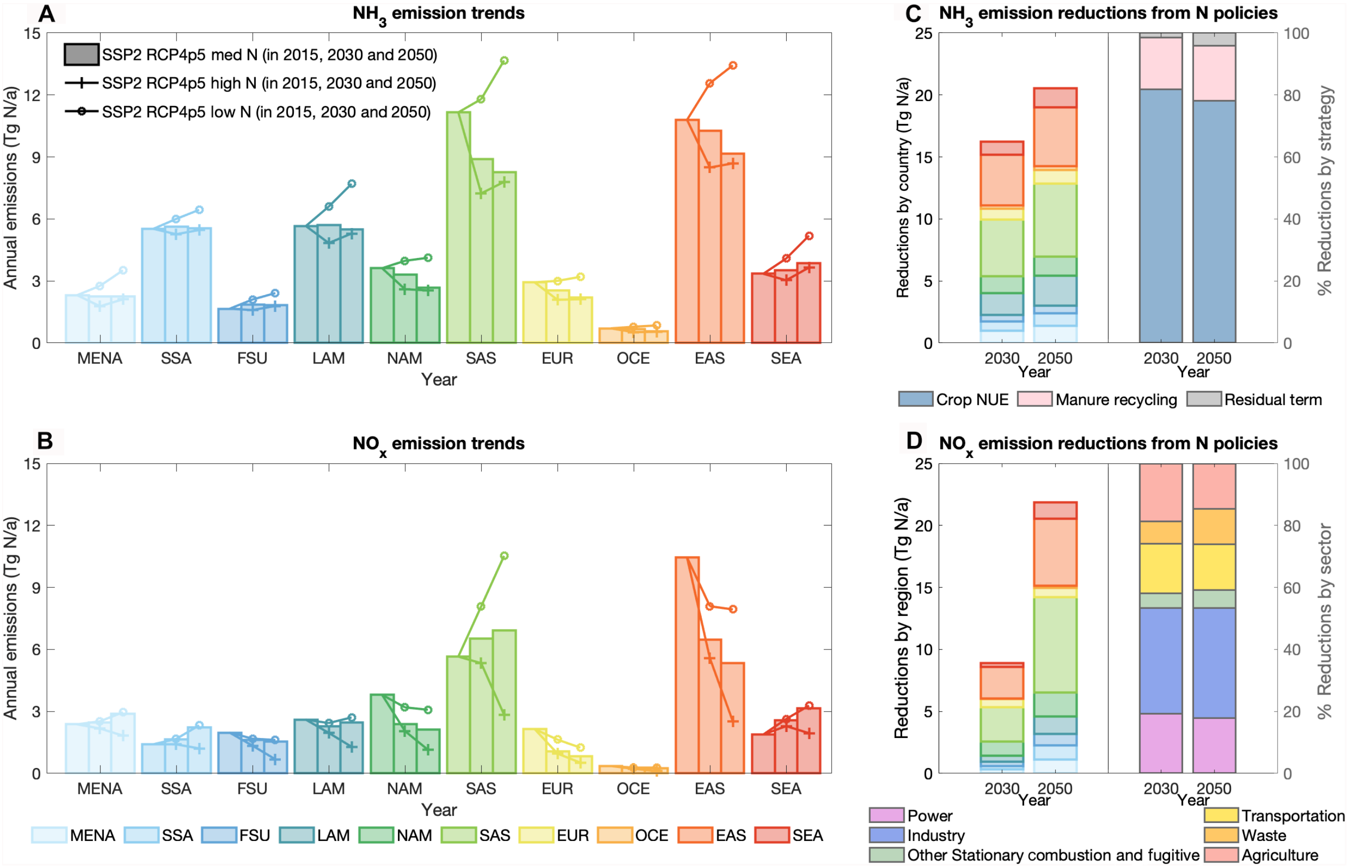

Fig. 2. Projected anthropogenic N_r (NH_3 and NO_x) emissions (unit, Tg N/a) under three INMS (socioeconomic-climate-nitrogen policy) scenarios, i.e., low-, medium-, and high-ambition nitrogen policy under SSP2-RCP4p5 in 2015, 2030, and 2050, and the effects of ambitious nitrogen interventions in reducing N_r emissions for major world regions (unit, Tg N/a) and contribution (unit, %) by sectors/strategies. (**A** and **B**) show trends of annual regional emissions (Tg N/a) for NH_3 and NO_x. Annual emissions are calculated for 10 global regions indicated by different colors, and three bars from left to right represent the years of 2015, 2030, and 2050. (**C** and **D**) illustrate reductions of NH_3 and NO_x emissions achieved through ambitious nitrogen policies by regions (left *Y* axis, in Tg N/a) and by strategy/sectors (right *Y* axis, in %).

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emissions are expected for most clean air legislation regions (i.e., East Asia, North America, Oceania, and Europe), even under low-ambition N policy scenarios, representing the fact that current climate policies targeting energy system transformation reduce greenhouse gas emissions as well as energy-related NO_x emissions. For developing regions, dramatic NO_x emission increases occur in Southeast and South Asia, with much smaller increases for Latin America and sub-Saharan Africa. Following the highly sustainable or polluting pathways, N_r emission changes between 2015 and 2050 further expand to −28 ~ +40% for NH_3 and −70 ~ +17% for NO_x (fig. S2). Emission reduction potentials of up to 28% globally for NH_3 as projected under the sustainable high-ambition nitrogen policy scenario were not seen in other published gridded emission projections for their lack of explicit representation of agricultural production- and consumption-side N interventions (fig. S3) (*38*, *39*).

Effects of aspirational N interventions are inferred from a shift from the low- to high-ambition nitrogen policy scenarios under SSP2-RCP4p5 (table S3). For agricultural NH_3, this means shifting from a continuation or even roll-back of historical trends [business as usual (BAU)] toward substantial improvements in crop system NUE and manure recycling rates, with differentiated paces and targets assigned for various country groups by 2030 and 2050 [as defined in Kanter *et al.* (*35*) and implemented into Global Biosphere Management Model (GLOBIOM); see Materials and Methods] achieved through improved management techniques (see table S1 and Fig. 2). For anthropogenic NO_x, this means shifting from a BAU condition toward maximum feasible reductions, i.e., full technological limits for NO_x controls are met regardless of costs. This means substantially improved combustion conditions through selective catalytic reduction techniques or non-catalytic selective reduction for stationary and mobile fossil fuel use [as implemented into Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS); see Materials and Methods (table S1 and Fig. 2)].

Nitrogen interventions would reduce global anthropogenic NH_3 emissions by 16 teragrams of nitrogen per annum (Tg N/a) in 2030 and 21 Tg N/a in 2050, representing 30% and 40% of emission levels in 2015 (Fig. 2C). The largest reductions occur in East and South Asia and are dominantly achieved by crop NUE improvements assumed under the high-ambition nitrogen interventions (contributing ~80% of total reductions). Adopting measures that increase manure recycling rates reduce NH_3 volatilization from manure while slightly increasing NH_3 emissions from cropland with more manure applied to soil because manure has a higher NH3 emission factor than nitrogenous fertilizer following the IPCC tier 1 default values (fig. S4). N interventions reduce global anthropogenic NO_x by 9 Tg N/a in 2030 and 22 Tg N/a in 2050, accounting for 21 and 52% of emission levels in 2015 (Fig. 2D). South and East Asia together contribute more than ~2/3 of the total reductions. The largest reductions occur in industry sectors, followed by power and transportation sectors.

Future air quality and human health benefits of N interventions

Reductions in N_r emissions improve $PM_{2.5}$ and O_3 air quality. We assess air quality under five INMS scenarios in 2030 and 2050 using a global atmospheric chemistry transport model Goddard Earth Observing System Chemistry (GEOS-Chem), projected emissions for N_r from ours and for non-N_r species from CMIP6 (Coupled Model Intercomparison Project phase 6; see Materials and Methods and fig. S5). We conduct baseline air quality simulation for 2015 serving as a benchmark. Simulated $PM_{2.5}$ and O_3 in 2015 compare reasonably well against observations indicated by previous research (*13*) and fig. S6, respectively.

We illustrate future population-weighted $PM_{2.5}$ and maximum daily 8-hour average (MDA8) O_3 concentrations (two metrics widely used for addressing public health impacts of air pollution) for major world regions in figs. S7 to S9. Following the $PM_{2.5}$ projections, South Asia will surpass East Asia by 2030 and become the top $PM_{2.5}$ hotspot hereafter, followed by sub-Saharan Africa and East Asia with almost equal $PM_{2.5}$ levels by 2050. Most regions will have improved $PM_{2.5}$ air quality, e.g., East Asia in particular; instead, South Asia and sub-Saharan Africa will experience elevated $PM_{2.5}$ levels owing to increased precursor emissions associated with economic development. For MDA8 O_3, South Asia has the highest pollution levels, followed by East Asia, Middle East and North Africa, and sub-Saharan Africa. Low-ambition N policy scenarios (both under SSP2-RCP4p5 and SSP5-RCP8p5) result in rapidly increasing O_3 concentrations in South Asia, sub-Saharan Africa, and East Asia, while high-ambition N policy scenarios (both under SSP2-RCP4p5 and SSP1-RCP2p6) lead to considerable decreases in O_3 levels. Regardless of INMS scenarios, developed regions will always have gradually mitigated $PM_{2.5}$ and O_3 pollution in the future (figs. S8 and S9).

Nitrogen interventions provide substantial air quality benefits, by reducing global population–weighted $PM_{2.5}$ by 3 μg/m^3 in 2030 and 6 μg/m^3 in 2050, and reducing global MDA8 O_3 by 1 part per billion by volume (ppbv) in 2030 and 4 ppb in 2050 (Fig. 3). Effects of N interventions on pollution mitigation are much larger in 2050 than 2030; such growth of effects over time is larger for O_3 than $PM_{2.5}$. High-ambition N policies would facilitate Southeast Asia and Former Soviet Union under SSP2 RCP4.5 to achieve the World Health Organization (WHO) Interim Target 4 for $PM_{2.5}$ (10 μg/m^3 for annual mean $PM_{2.5}$), East Asia to achieve Interim Target 1 (35 μg/m^3) (fig. S8), sub-Saharan Africa to achieve Interim Target 1 for O_3 (80 ppbv for 99th percentile annual MDA8 O_3), and Latin America to achieve WHO's O_3 Air Quality Guideline (50 ppbv) by 2050 (table S4).

Reduced exposure to air pollution owing to nitrogen interventions provides human health benefits. We estimate premature deaths associated with $PM_{2.5}$ and O_3 under INMS scenarios both using future gridded SSP-specific population projections and populations fixed at 2015 levels (fig. S10; see Materials and Methods), so influences of both population growth and pollutant concentrations can be characterized. For regions with large population growth rates (fig. S7C), such as sub-Saharan Africa (+83 ~ +113% between 2015 and 2050) and South Asia (+28 ~ +46%), their future air pollution–related premature mortality increases more substantially factoring in population growth (fig. S10). For most regions except for East Asia and the former Soviet Union, considering future population changes also would increase the estimated health benefits of N interventions (Fig. 3). Globally, nitrogen interventions would avoid $PM_{2.5}$-related premature deaths by 357 k in 2030 and by 697 k in 2050, assuming fixed populations; such benefits further increase to 398 k, avoiding premature deaths in 2030 and 817 k in 2050 when population growth is considered. The 817 k that avoided premature death are equivalent to ~16% of $PM_{2.5}$-related human disease burdens in 2015. Similarly, the benefits of nitrogen interventions for avoiding premature deaths associated with O_3 increase from 207 to 252 k (34% of O_3 health impacts in 2015) in 2050, when factoring in population growth. These health benefits mainly occur in Asia, i.e., East Asia and South Asia altogether contribute to ~627 k (77% of global totals), and ~184 k (73%) avoided $PM_{2.5}$- and O_3- related premature deaths, respectively, in 2050.

Reductions in air pollution–related crop yield losses and nitrogen deposition–related risks of biodiversity loss

Nitrogen interventions save crop yields by reducing crop exposure to O_3 pollution and the risks of ecosystem biodiversity losses by reducing excess nitrogen deposition harmful to sensitive ecosystems. These impacts are quantified using concentration-response relationships and nitrogen deposition critical load maps (see Materials and Methods). Globally, shifting from low- to high-ambition N policy under SSP2-RCP4p5 helps reduce yield losses of major crops (i.e., maize, wheat, rice, and soybean) by 31 million tons in 2030 and 99 million tons in 2050 assuming that yields are fixed at 2015 levels. Such benefits further increase to 36 million tons in 2030 and 122 million tons in 2050 when accounting for scenario-specific future yield changes projected by GLOBIOM representative of both impacts of productivity improvements and climate (Fig. 4). The 122–million ton yield loss avoided equals 4.3% of global yield levels in 2015.

At the global scale, yield benefits of nitrogen interventions are almost equal for maize, rice, and wheat. Distribution of benefits among crops is much more unbalanced at regional scales, e.g., dominated by wheat in the Middle East and North Africa, Europe, and the former Soviet Union; by rice in South and Southeast Asia; by maize in East Asia and North America; and by soybean in North America and Latin America. The largest yield benefits occur in East Asia and North America, contributing to ~41% (43%) and ~28% (21%) of the global benefits in 2030 (in 2050), respectively. For regions where yields are projected to increase notably during 2015–2050, such as Latin America, the Middle East and North Africa, South Asia, and sub-Saharan Africa (fig. S11A), N interventions and associated O_3 mitigation are more critical in reducing yield losses than those for other regions since O_3 concentration reductions would protect an additional large number of crops from yield damages (Fig. 4). South Asia is an exception; in the short term by 2030, N interventions even increase net yield losses by 1.4 million tons, largely driven by higher wheat yield losses. This is because in polluted regions, NO_x reductions alone [without controlling another precursor of O_3, i.e., volatile organic carbon compounds (VOCs)] will first increase O_3 levels by reducing the titration effects, i.e., excess NO_x in 2015 consumes O_3, and with decreased NO_x in 2030, O_3 increases. As a result, the high-ambition N policy scenario compared to the low-ambition N policy scenario,

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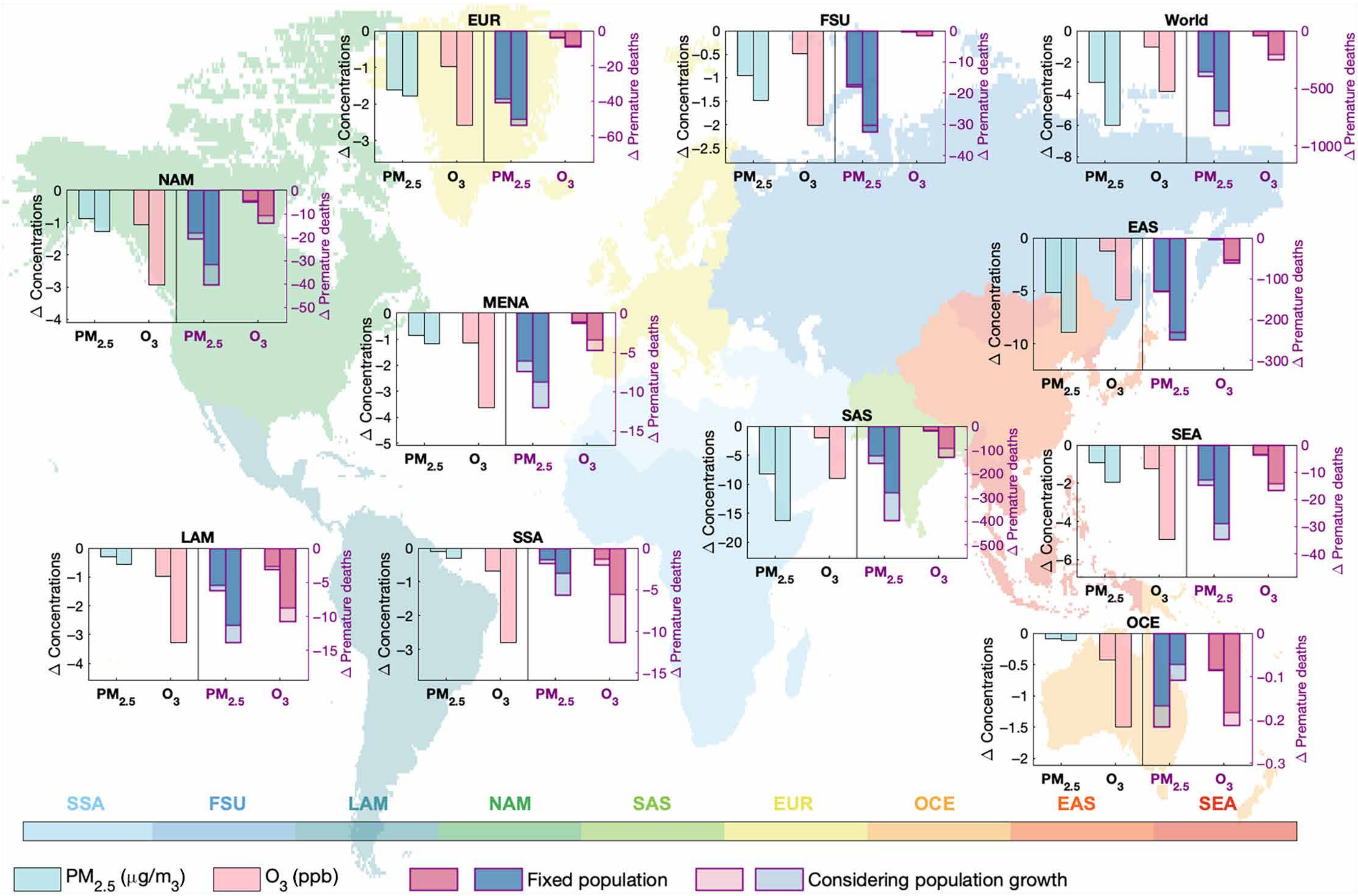

Fig. 3. Effects of N interventions under SSP2-RCP4p5 in mitigating regional $PM_{2.5}$ (unit, μg/m^3) and O_3 concentrations (unit, ppbv; left *Y* axes) and air pollution–related premature deaths (unit: k persons; right *Y* axes) in 2030 and 2050. Results are shown for each region and the world for population-weighted $PM_{2.5}$ (bars in light blue), MDA8 O_3 (bars in light pink), and $PM_{2.5}$ and O_3-related premature deaths (bars in blue and pink, respectively). Each cluster consists of two bars that represent effects for 2030 and 2050 from left to right. Future premature mortalities are presented assuming fixed populations at 2015 levels (bars in solid colors) with effects of representing future population growths also shown (bars in translucent colors).

despite having lower regional averaged MDA8 O_3, turns out to have higher AOT40 value [aggregated hourly surface ozone concentrations during the local daylight (08:00 to 19:59) above the threshold of 40 ppb] for wheat in India, indicative of enhanced O_3 exposure during maize-growing season (fig. S12). Such impacts are modulated—moving from 2030 to 2050— and by 2050, a net yield benefit is expected, i.e., N interventions avoid 21.5–metric ton reductions of yield losses in South Asia.

Large amounts of forest and grassland areas benefit from reduced N deposition allowed by N_r emission mitigation. In 2015, nearly 300 Mha of the terrestrial ecosystem in East Asia and 120 Mha in South Asia suffer from exceedances of nitrogen critical load and potential losses of biodiversity (fig. S11). Implementing medium- or high-ambition nitrogen policy under SSP2 RCP4p5 would increasingly mitigate such critical load exceedances (fig. S11). Globally, shifting from low- to high-ambition N policy under SSP2-RCP4p5 reduces ecosystem areas that have N deposition exceeding N critical loads by 260 Mha in 2030 (equivalent to 43% of exceedance areas in 2015) and 420 Mha in 2050 (69%). Ecosystems in East Asia, North America, the former Soviet Union, South Asia, and Latin America show the largest benefited areas of 89, 74, 63, 56, and 40 Mha, respectively, in 2050.

Opportunities of nitrogen interventions for accelerating sustainable development

There exist substantial yet unquantified potentials of nitrogen interventions in achieving multiple [Sustainable Development Goal (SDGs) (*40*)], including SDG 3, Good Health and Well-being; SDG 2, Zero Hunger; SDG 12, Responsible Consumption and Production; and SDG 15 Life on Land. We compare performance of various INMS futures to the benchmark condition (year 2015) and find that nitrogen interventions are crucial to prevent several environmental and human health objectives from deteriorating, especially when future population and crop yield changes are considered (Fig. 5). Following the SSP2 RCP4p5 pathway toward 2050, to keep N deposition–threatened ecosystem and O_3-related deaths below the 2015 threshold level, high-ambition N policies have to be implemented (Fig. 5A). The highly sustainable scenario, i.e., high-ambition N policy under SSP1 RCP2p6, maintains all environmental metrics below 2015 levels (Fig. 5B). The highly polluting scenario, i.e., low-ambition N policy under SSP5 RCP8p5, instead, fails to maintain the 2015 levels in almost all ecosystem and human health metrics (Fig. 5C). Following the SSP2-RCP4p5, low-ambition N policy trajectory is slightly better, but environmental burdens still exacerbate during 2015–2050 (Fig. 5C). Notably, Fig. 5

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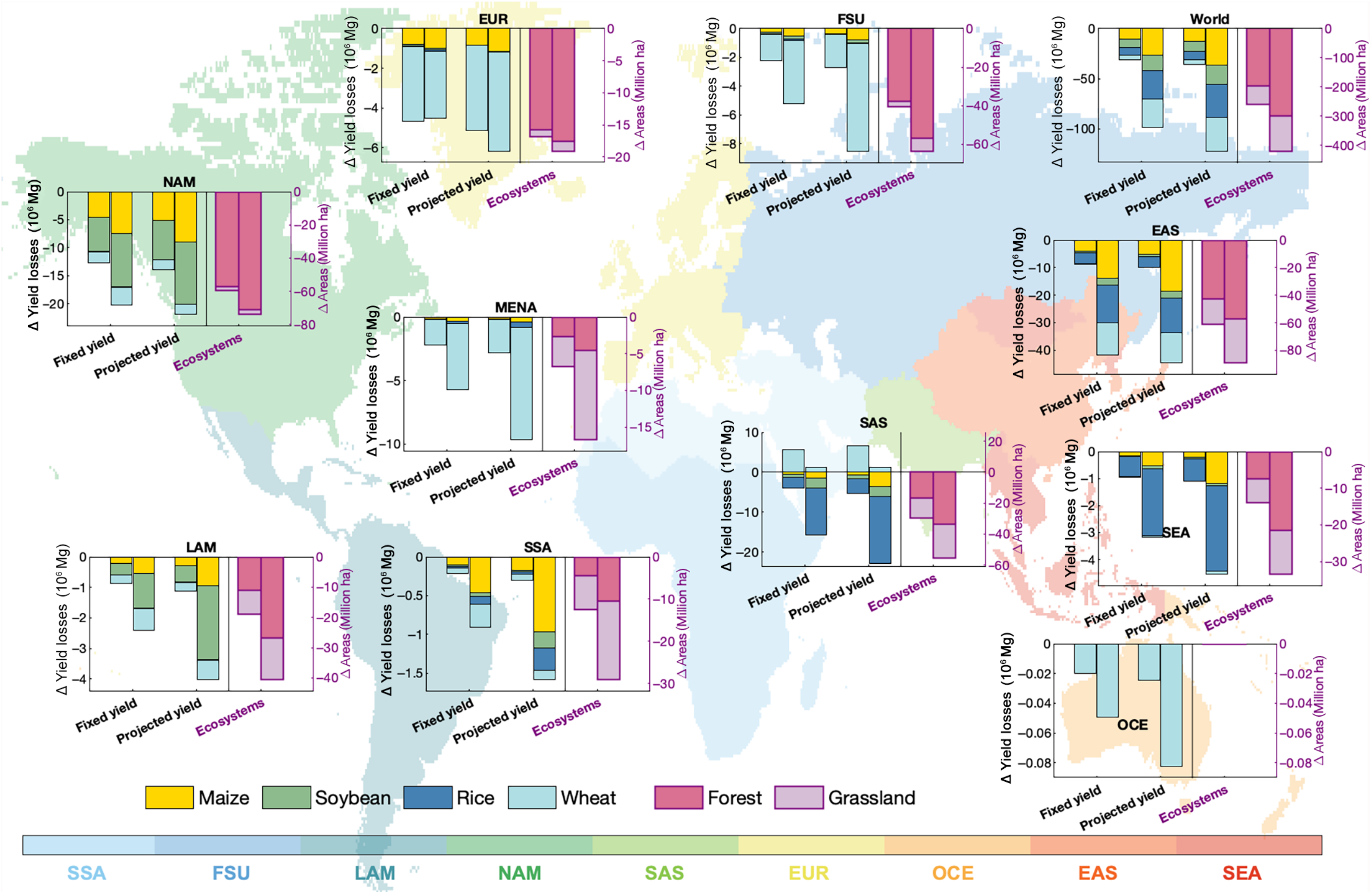

Fig. 4. Effects of aspirational nitrogen interventions in reducing crop yield losses associated with exposure to O_3 pollution (unit, 10^6Mg; left *Y* axes) and in reducing ecosystem areas (unit: 10^6ha; right *Y* axes) that have nitrogen deposition above critical N deposition rates to limit terrestrial biodiversity loss in 2030 and 2050. Yield effects are decomposed for losses for maize, soybean, rice, and wheat, and ecosystem effects are decomposed for forests and grassland. Each cluster consists of two bars representing effects in 2030 and 2050 from left to right.

assumes fixed future population numbers and yields at 2015 levels. When considering their future changes, only the INMS scenarios that have high-ambition N policies can keep future $PM_{2.5}$ and O_3 health burdens and crop yield losses below the 2015 levels (fig. S13, B versus C). Our results for low-ambition N policy scenarios are consistent with earlier findings that population growth, rather than air pollutant concentration changes, would dominate future air pollution health impacts (*41*). However, with high-ambition N policies, such impacts can be substantially reduced.

Climate policies alone can still largely benefit $PM_{2.5}$ management by providing emission reductions of NO_x, other aerosol precursors (i.e., SO_2), and primary $PM_{2.5}$ through clean energy transitions. Apart from that, N policies are more effective in reducing N_r impacts than climate policies. This is seen in Fig. 5 that, except for $PM_{2.5}$, shifting from low- to high-ambition N policies but maintaining SSP2-RCP4p5 settings (Fig. 5A) imposes larger impacts than merely changing SSP-RCP settings but maintaining N policy ambitions (Fig. 5, B and C).

While we find considerable benefits of nitrogen interventions at regional and global scales, local disparities exist. Locally, the benefits of nitrogen interventions can be more substantial than those seen as regional averages, e.g., up to 20–μg/m^3 reductions in $PM_{2.5}$ in northeastern India (fig. S14) and up to 12-ppbv reductions in MDA8 O_3 in some areas near the equator in 2050 (fig. S15). Some hotspot areas may even see disadvantages, e.g., parts of the North China Plain may experience up to 3-ppbv increase of O_3 in 2030 likely owing to reduced titration effects. For parts of India, wheat production may experience increased O_3 exposure during its growing season (but not other major grain crops) also owing to reduced titration effects (fig. S12). This emphasizes the need for simultaneous VOCs control or deeper NO_x controls to avoid increased O_3 pollution. More regional details in projected $PM_{2.5}$ O_3 air quality and nitrogen deposition across future INMS scenarios can be found in figs. S16 to S18. Features at fine geographical resolutions have important implications for environmental justice (*27*, *28*, *42*, *43*).

DISCUSSION

Environmental and health benefits of aspirational nitrogen interventions demonstrated here remain conservative. Nitrogen interventions can potentially provide benefits for climate and water (and thus for SDG 13 Climate Action and SDG 14 Life Below Water). Agricultural greenhouse gas mitigation from nitrogen interventions reaches 400 metric tons CO_2-eq/a by 2050, and water pollution mitigation

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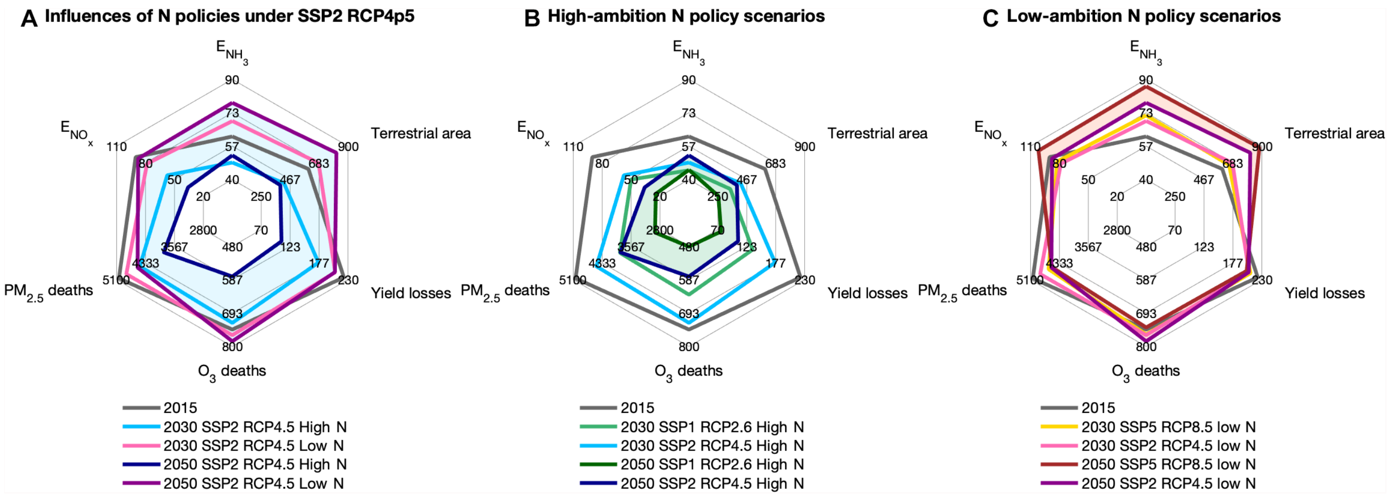

Fig. 5. Environmental and health metrics under 2015 and five INMS scenarios in 2030 and 2050. The six metrics include anthropogenic NH_3 emissions (E_{NH3} , unit, Tg N/a) and NO_x emissions (E_{NOx}, unit, Tg N/a), premature deaths associated with human exposure to $PM_{2.5}$ and O_3 (unit, k persons), crop yield losses of major crops (maize, wheat, rice, and soybean) associated with exposure to O_3 (unit, metric tons), and terrestrial areas that have N deposition exceeding critical loads (unit, Mha). (**A**) illustrates the influences of nitrogen interventions by shifting from low- to high-ambition N policy under SSP2 RCP4p5. (**B**) compares two high-ambition N policy scenarios. (**C**) compares two low-ambition N policy scenarios. The shaded areas denote the benefits of shifting from low- to high-ambition N policies in 2050.

(*44*) (i.e., reduction in N_r runoff/leaching) reaches 30 metric tons NO_3^- N/a by 2050, as projected by the GLOBIOM model (Nr emission/loss reductions by comparing those under SSP2 RCP4p5 high- and low-ambition N policy scenarios) but are out of the scope of this study. In addition, nitrogen interventions such as decreasing manure N excretion rate through changing animal diets were implicitly accounted for by the GLOBIOM model through endogenous shifting livestock production systems as part of the SSP-RCP scenario assumptions, and, thus, its effect was not evaluated here (see the section "Uncertainty analyses") (*45*). Effects of N_r interventions on N_2O emission reduction and thus stratospheric ozone conservation and human health protection (*46*, *47*) are not considered because of large uncertainties and their smaller health impact compared to air pollution. Joint health impacts of NO_2 in addition to $PM_{2.5}/O_3$ are also excluded here. Human exposure to NO_2 also causes premature deaths and might need to be included to fully characterize the toxicity of the atmospheric mix (*45*, *48*). Here, we follow the Global Burden of Disease study approach that solely addresses $PM_{2.5}$ and O_3 because epidemiological studies have not evaluated the joint effects of these pollutants and risks may not be fully additive and because model-simulated NO_2 requires future careful evaluation against measurements since NO_2 has a rather short lifetime (minutes to hours) and may transform quickly between NO and NO_2.

There exist other N_r impact pathways unquantified here that potentially provide a trade-off. For total nitrogen input scarce regions, atmospheric deposition provides a critical nitrogen input into cropland, forests, and open oceans. Thus, future N_r emission abatement and reduced deposition could potentially negatively affect crop yields (e.g., in Africa assuming insufficient fertilizer N application) and ocean productivity. Such effects potentially could be evaluated using crop yield response to total nitrogen input curves (*49*, *50*) and the Redfield ratio (*51*, *52*). For this study, N deposition impact on yield is not relevant, as GLOBIOM (like all other integrated assessment models) uses a nitrogen budget approach to ensure that sufficient nutrients are applied to ensure crop and pasture production.

To avoid anecdotal integrated N_r assessment, research needs to balance comprehensiveness (multiple objectives) and relevance to human and ecosystem welfare (some objectives are less important for the society than others). Our research calls for future work that could be more policy-relevant by monetizing various N_r impact (*14*), or by grouping end points (e.g., to loss of life years, biodiversity loss, primary production of food commodities, and net global warming effect), or by applying proxies such as distance to policy targets to better understand to what extent nitrogen interventions could help achieve multiple environmental/health targets (compared to other approaches). Identifying the most relevant impacts of N_r under different time frames and in different local contexts is challenging but critical. We heavily focus on impacts of atmospheric pollution and deposition on human health, vegetation, and ecosystems, in different regions of the world, based on earlier findings that air quality and ecosystem impacts are the most socially damaging impact pathway of N_r (*8*, *53*). Currently, a major global synthesis effort to compile knowledge on nitrogen and its environmental impacts under the INMS project is expected to deliver the International Nitrogen Assessment (INA) report by 2025. INA would provide a thorough and comprehensive evaluation of environmental/health benefits of halving nitrogen waste in all directions through multi-model approaches.

In sum, our analyses unveiled potentials of future global aspirational N_r interventions for achieving NH_3 and NO_x emission reductions and thus for improving $PM_{2.5}$ and O_3 air quality and mitigating excess nitrogen deposition, which would avoid human premature deaths and crop yield losses related to air pollution and decrease ecosystem risks of biodiversity losses. In the absence of integrated N_r management (i.e., under low-ambition N policy future scenarios), environmental and health objectives examined here will deteriorate by 2030 and 2050 (compared to the present). Exploiting such co-benefits, instead, by removing socioeconomic/political barriers against aspirational nitrogen interventions for their implementation (see the section "Uncertainty analyses") can substantially increase policy successes toward clean air and human health, and benefits increase from 2030 to

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2050. Nitrogen interventions would help accelerate global progress toward achieving multiple SDGs (including SDG 3 Good Health and Well-being, SDG 12 Responsible Consumption and Production, and SDG 15 Life on Land).

MATERIALS AND METHODS

Future socioeconomic-climate-nitrogen policy storylines (INMS scenarios)

Air quality studies widely adopt future emission projections from the CMIP, i.e., the SSP-RCP future scenarios that primarily mimic influences of climate mitigation policies (expressed as RCPs) in socioeconomic contexts (expressed as SSPs) (*38*). Each CMIP6 scenario consists of an SSP and an RCP component and provides estimations of global gridded anthropogenic emissions (such as organic carbon, black carbon, VOCs, CO, NO_x, CH_4, SO_2, etc.) for every 5-year interval between 2015 and 2100 (*38*).

To tackle the N_r challenge, Kanter *et al.* (*35*) conceptualized an analytical framework for global futures that integrates N_r pollution abatement measures and policies within the traditional climate-centered SSPs-RCPs framework. This recently added nitrogen policy dimension is critical because the nitrogen problem is challenging to manage and has many analogies with the carbon (climate) problem (*8*, *36*, *37*). The global planetary boundary for the biogeochemical cycle of nitrogen has been substantially exceeded owing to energy and food production activities, generating a broad range of cascading damages to air and water quality, ecosystem biodiversity, soil health, stratospheric ozone, and climate.

Kanter's framework specifically adds N abatement interventions at different ambition levels with quantitative targets (e.g., crop NUE) specified for various country groups based on climate mitigation scenarios. These scenarios are intended for the "Towards the Establishment of an International Nitrogen Management System – INMS" project and thus are abbreviated as INMS scenarios. The INMS scenarios are developed as part of the INMS (https://inms.international) project funded by the Global Environment Facility/UN Environmental Program that promotes scientific and policy innovations to establish international integrated management of the Earth's nitrogen cycle.

There are seven INMS scenarios in total. Assumptions are that the stringency of nitrogen interventions are conditional upon SSP-RCP combinations, e.g., high-N pollution intervention policy ambitions only exist in sustainable futures of SSP1-RCP2p6 and SSP1-RCP4p5 and middle-of-the-road future of SSP2-RCP4p5. In contrast, low-N policy ambitions only exist in the unequal development futures of SSP5-RCP8p5 and middle-of-the-road future of SSP2-RCP4p5. Table S2 lists the five INMS scenarios included in this study; the other two scenarios excluded are high-ambition N policy and high-ambition N policy plus dietary transitions under SSP1 RCP4p5. Because the CMIP6 system does not have an SSP1-RCP4p5 scenario where non-N_r species' emission projections can be obtained, we excluded these two INMS scenarios. The five INMS scenarios used are sufficient to illustrate variations of N policy ambitions under SSP2-RCP4p5 and represent lower and upper bounds for future possibilities.

N policy ambitions are represented as nitrogen interventions toward crop, livestock manure excretion, manure cycling, air pollution, and wastewater sectors, which are expected to reduce N_r losses to the environment in the forms of NH_3, NO_x, N_2O, and NO_3^- -leaching and runoff. Representation of low, medium, and high policy ambitions is defined separately for The Organization for Economic Cooperation and Development (OECD), non-OECD high-income countries and non-OECD low-income countries [see Kanter *et al.* (*35*)]. Indicators of crop NUE and nitrogen surplus are used for the crop sector. High (medium) N policy ambitions require OECD countries to achieve target NUE by 2030 (by 2050), non-OECD high-income countries to achieve NUE in 10 years (30 years) after catching up with OECD countries, and non-OECD low-income countries in 30 years after catching up with OECD countries (follows historical trends over 30 years before improving). Low-N policy ambitions allow OECD countries to have constant NUE, non-OECD high-income countries to follow historical trends if they have been decreasing otherwise NUE is constant, and non-OECD low-income countries follow decreased NUE trends as countries in similar socioeconomic status. Detailed assumptions for manure generation, cycling, air pollution, and waste management can be found in Kanter *et al.* (*35*).

Estimating future agricultural NH_3 emissions in INMS scenarios

This research adopts the International Institute for Applied System Analysis (IIASA) GLOBIOM and an extended nitrogen cycling module developed by Chang *et al.* (*3*) to generate gridded agricultural NH_3 emission estimates for five future INMS scenarios. GLOBIOM is a global land sector economic equilibrium model that analyzes the implications of global agriculture, forestry and bioenergy production, consumption and trade on land competition, resource uses (water and fertilizers), food security, and pollutant releases (N_r, greenhouse gas emissions, etc.) (*54*–*56*).

The principal variable characterizing the livestock production in GLOBIOM is the number of animals by species, production system and production type in each simulation unit.

Each livestock category is characterized by product yield (meat, milk, and egg) and feed requirements. The feed requirements for ruminant are calculated at the level of four aggregates—grains (concentrates), stover, grass, and other using the RUMINANT model [Herrero *et al.* (*57*)]. When estimating the feed-yield couples, the RUMINANT model takes into account different qualities of these aggregates across regions and systems. Feed requirements for monogastrics are at this level determined through literature review presented in Herrero *et al.* 2013. That is to say in the GLOBIOM, animals in different production systems have different diet and thus different manure N excretion. For livestock dynamics, the number of animals of a given species and production type (meat or milk for ruminant and meat or eggs for poultry) in a particular production system and supply unit is an endogenous variable. This means that it will decrease or increase in relation to changes in demand and the relative profitability with respect to competing activities. Therefore, as part of the SSP-RCP scenario assumptions [O'Neill *et al.* (*58*)], the socioeconomic pathways drive the demand and supply those endogenous shifting livestock production systems. For detail of the GLOBIOM model description, structure, and in particular for the livestock system transitions, please refer to Havlik *et al.* (*59*).

In this study, INMS scenarios are implemented in GLOBIOM. SSPs determine GDP, population growth rate, dietary patterns, and trade policies. RCPs determine the magnitude of bioenergy production, which competes for land use with food production. Nitrogen interventions happen by influencing crop system NUE, manure recycling rate, and associated losses and emissions. Crop system NUE measures the ratio of crop nitrogen harvested in total nitrogen inputs into

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cropland, including fertilizer, manure, irrigation, atmospheric deposition, and biological fixation.

Under the high-ambition N policy scenarios, 1) crop NUE is projected to reach the target proposed by Zhang *et al.* (*60*) for country groups (OECD, non-OECD high-income countries, and non-OECD low-income countries) by 2030 (with linear progression starting in 2010) and subsequently kept constant; 2) the share of manure collected into confinement and allocated to other uses than recycling into cropland and pasture (varies between livestock production system and regionally between 0 and 55% for 2010) is capped to 10% by 2030 (with a linear progression toward that target starting in 2010 if higher than 10% in the baseline and kept constant if lower than 10% in the baseline); 3) losses of manure collected into confinements are reduced by 50% in 2030 (with a linear progression toward that target starting in 2010); 4) ammonia emissions were scaled proportionally to the N surplus, implying that with higher crop NUE, the ammonia emissions from manure and fertilizer spreading are reduced. For the medium-ambition N policy scenarios, the assumptions of future nitrogen management would reach the same level as that in the high-ambition N policy scenarios but 20 years slower (reaching targets by 2050). For the low-ambition N policy scenarios, the NUE, manure recycling rate, and manure losses are kept constant and no adjustments or reductions per N input on ammonia emissions compared with the 2010 level.

The nitrogen cycling module within GLOBIOM budgets food system nitrogen flows and parameterizes NH_3, N_2O, nitrate-leaching, and runoff emissions at grid levels and has shown good comparison against other global agricultural NH_3 inventories (*3*). Emissions generated are gridded at 0.5° latitude and longitude resolution every 10 years between 2010 and 2100. Emissions for 2030 and 2050 are used. Ammonia emissions were scaled proportionally to the N surplus, implying that with higher crop NUE, the ammonia emissions from manure and fertilizer spreading are reduced.

Estimating future NO_x emissions in INMS scenarios

We use the GAINS model to estimate country- and sector-specific anthropogenic NO_x emissions under future INMS scenarios. The GAINS model has been widely used for policy-oriented research on all-sector control technologies and costs, emission reduction potential, and consequent climate and air quality benefits (*61*). It includes major air and climate pollutants, i.e., PM ($PM_{2.5}$, PM_{10}, organic carbon, black carbon, and organic matter), SO_2, NO_x, NH_3, VOCs, N_2O, CH_4, CO_2, CFCs, CF_4, and HFCs. It represents emission processes based on statistics and data on sectoral/fuel activities, emission factors, end-of-pipe control technologies, and technological adoption costs for major countries and regions worldwide.

GAINS takes advantage of external projections of the development of economic commodities. For NO_x emissions, energy and industry projections are needed. Here, we took advantage of data from the World Energy Outlook (*62*) in three different scenarios: "current policies," "new policies," and "sustainable development" (these policies reflect climate policies inconsiderate of pollution). We understand that the current policies scenario most closely resembles an INMS scenario without climate mitigation, the new policies scenario reflects moderate climate mitigation, and the sustainable development represents a high climate mitigation scenario in INMS (see Fig. 1).

GAINS also allowed adequately covering the nitrogen policy levels (low, medium, and high ambitions) defined by Kanter *et al.* (*35*). Here, GAINS can quantify emissions of a future situation assuming that abatement technology is in place at a given level (*63*). Emissions of NO_x are reduced by applying measures such as modified (improved) combustion conditions, selective catalytic reduction techniques, or non-catalytic selective reduction including reducing agents. We understand that the low policy ambition reflects a continuation of the current situation without adding further emission controls (extrapolating trends "no further control"). For medium policy ambition, we understand that at least emission reductions that have been put forward on a policy agenda are being implemented at the proposed level. We call these "current legislation" not allowing for any slip in ambition that accompanies such legal proposals in practice. The high policy ambition then aligns with maximum technically feasible reduction currently implemented in GAINS.

Future non-N_r anthropogenic emissions

Anthropogenic emissions of non-N_r species are from the CMIP6 SSP-RCP database, including monthly anthropogenic emissions for black carbon (BC), methane (CH_4), carbon monoxide (CO), organic carbon (OC), sulfur dioxide (SO_2), and various VOCs species in 2030 and 2050. Emissions for the same RCP-SSP combinations as the above INMS settings in the CMIP6 scenarios are selected.

Estimating $PM_{2.5}$ and O_3 air quality in 2015, 2030, and 2050

We use the GEOS-Chem 3D model version 12.9.3 to analyze present and future air quality. Metrics of regional population–weighted $PM_{2.5}$ concentrations and MDA8 O_3 concentrations have been adopted for their great relevance to public health. GEOS-Chem air quality simulations are conducted for the baseline year (2015) and for the future (2030 and 2050) under five INMS scenarios' emission projections. Simulations are driven by assimilated meteorological fields from NASA's Modern-Era Retrospective Analysis for Research and Applications, version 2 for 2015. GEOS-Chem has widely been applied to air quality research and shows reasonable agreements between observations and modeled $PM_{2.5}$. Version 12.9.3 has several improvements, including updated ISORROPIA v2.2, improved isoprene (*64*–*69*), and an improved deposition scheme for HNO_3 and particulate nitrate (*70*). For the 2015 baseline simulation, the Community Emissions Data System (CEDS) emission inventory (*71*) is used for anthropogenic emissions. Natural emissions include NO_x from soil and lightning, NH_3 from soil and seabirds, as well as biomass burning emissions from the Global Fire Emissions Database (GFED4) (*72*) in 2015.

For future simulations, we conduct 10 simulations in total representing five INMS scenarios (table S2) and 2 years (2030 and 2050). Anthropogenic NO_x emissions are from 2015 CEDS NO_x multiplied by trends indicated by GAINS. Agricultural NH_3 emissions are from 2015 CEDS NH_3 multiplied by trends indicated by GLOBIOM. GLOBIOM's 2015 emission estimate is from interpolations between 2010 and 2020 since the model is run at a 10-year time step. Natural emissions and meteorology in future simulations are the same as that in 2015. This is a suitable and typical approach [e.g., as used by Cheng *et al.* (*73*) and Zhou *et al.* (*74*)] since the most recent IPCC report finds that changes in precursor emissions are the primary driver of future changes in air quality as opposed to climate change (*75*). Future anthropogenic emissions of other non-N_r species are directly from CMIP6 projections since CMIP6's estimate for 2015 has largely been harmonized with CEDS 2015 emissions.

Each simulation is for 1 year after a 4-month spin-up with a horizontal resolution of 2° × 2.5° and a vertical resolution of 47 layers. The 2° × 2.5° resolution is widely used for global $PM_{2.5}$ studies (*76*–*79*)

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and IPCC's global future $PM_{2.5}$ projections (*80*, *81*), and is thus sufficient for estimating regional air quality.

Estimating public health impacts of exposure to $PM_{2.5}$

Assessments of the human health burden of exposure to ambient $PM_{2.5}$ have been through epidemiological cohort studies that link premature mortality to long-term exposure of $PM_{2.5}$. Here, we use the Global Exposure Mortality Model (GEMM) to estimate premature deaths of noncommunicable diseases (NCDs) and lower respiratory infections (LRIs) due to human exposure to certain levels of $PM_{2.5}$ (*82*). GEMM has been widely applied to quantify human disease burdens imposed by exposure to $PM_{2.5}$ (*74*, *83*, *84*). GEMM calculates the relative risks (RR) of NCDs and LRIs associated with $PM_{2.5}$ exposure for adults (≥25 years old), with age groups in 5-year intervals from 25 to greater than 85 via

$$RR(c) = e^{\frac{\theta * \ln\left(\frac{z}{\alpha}+1\right)}{1+e^{-\frac{z-\mu}{\nu}}}}, z = \max(0, c - 2.4)$$

where c is long-term ambient $PM_{2.5}$ concentration; θ, α, μ, and ν are parameters that determine the shape of the concentration-response relationships estimated by the GEMM model (*82*); and 2.4 μg m^{-3} is the $PM_{2.5}$ threshold below which no effect occurs.

The reduction in premature deaths in each scenario can be estimated using

$$\delta Mort_{i,j} = Pop_{i,j} * Base_i * \left(\frac{1}{RR_{scenario,i,j}} - \frac{1}{RR_{base,i,j}}\right)$$

where $\delta Mort_{i,j}$ is the avoided premature mortality in our scenario compared to the base case for age group i in a GEOS-Chem grid j; $Pop_{i,j}$ is the number of population within age group i in grid j; $Base_i$ is the national average mortality rate of NCDs and LRIs in 2015 for age group i; $RR_{scenario,i,j}$ and $RR_{base,i,j}$ are the relative risks of NCDs and LRIs for age group i, in grid j, at $PM_{2.5}$ exposure level in the scenario and the base case, respectively. Data of global gridded population counts and population by age and sex for 2015 are derived from the Global Population for the World dataset provided by NASA Socioeconomic Data and Applications Center (*85*). National mortality rate and age distribution data are both retrieved from the Global Burden of Diseases study (http://ghdx.healthdata.org/).

For 2030 public health analyses, given the lack of future baseline mortality rate projection, we use 2015 baseline mortalities. For population, we use 1 km of SSP-specific population data in 2030 and 2050 reported by Wang *et al.* (*86*), while future age distribution are assumed to remain as in 2015. We also calculate health impacts assuming that population remains as 2015, a comparison that helps discriminate effects of population growth and pollution concentration changes in future health burdens.

Estimating public health impacts of exposure to O_3

The relative risk of long-term ozone exposure to human health through end point disease of COPD (chronic obstructive pulmonary disease) is estimated using the exposure-response function via (*87*, *88*)

$$RR(c) = e^{\beta(c - c_0)}$$

where c is the annual average of surface MDA8 ozone concentration, and c_0 equals 26.7 ppb representing the minimum level of annual MDA8 ozone exposure that poses no risk to human health (*89*). The exposure-response parameter, β, was derived from cohort studies (*89*). For ozone, we use baseline mortality rate at country level for COPD for all ages and genders in 2019 from the Global Health Data Exchange database (http://ghdx.healthdata.org/).

Estimating crop yield losses associated with exposure to O_3

We use a concentration-based approach to estimate damaging effects of surface ozone pollution on four major staple crops: maize, soybean, wheat and rice (*20*). The concentration-based metric *AOT40* (in units of parts per million per hour) is defined as aggregated hourly surface ozone concentrations during the local daylight (08:00 to 19:59) above the threshold of 40 ppb:

$$AOT40 = \sum_{t=1}^{N} \left(C_{O_3,t} - 40\right)$$

We calculate the cumulative *AOT40* exposure during the growing season period, which spans from 104 to 14 days before the start of the harvesting date. The harvesting date is determined using the global crop calendar dataset of major crops, with a resolution of 0.5° longitude by 0.5° latitude (*90*). Then, the relative yield (*RY*) of four main crop types, denoted by i, from ozone exposure was estimated following the exposure-yield relationship as

$$RY_i = 1 - \gamma_i AOT40$$

Here, RY_i represents the ratio of crop yields exposed to ozone pollution to those without ozone exposure. The coefficients γ_i are derived through constructing relationship between *AOT40* metric and crop field experiment, which were 0.0163, 0.0415, 0.0113, and 0.0356 for wheat, rice, soybean, and maize, respectively (*91*, *92*). Then, the yield loss of crop production (L_i) is estimated by the difference between the theoretical production (P_i/RY) and the actual production P_i following

$$L_i = \frac{P_i}{RY_i} - P_i$$

The crop productions P_i in 2015 are obtained from the Global Agro-Ecological Zones version updated to 2015 (GAEZ+_2015) dataset (*93*). This dataset downscales the original crop production statistics, obtained from the Food and Agriculture Organization dataset at the country level, into 5–arc min grid cells. We then regrid the data to 2.5° longitude by 2° latitude. We also estimated the yield loss in 2030 and 2050 based on predicted ozone exposure and crop productions, while other parameters remained the same. We first calculated the changing ratio of crop production from 2015 to 2030 and 2050 at country level using data from GLOBIOM. Such change ratio is then applied to the gridded crop productions in the baseline year 2015 to derive the predicted crop productions at 2.5° longitude by 2° latitude.

Estimating ecosystem areas affected by N deposition

GEOS-Chem–simulated deposition of N species is first downscaled to 0.1° resolution following methodology used in Guo *et al.* (*13*). We follow the method of Schulte-Uebbing *et al.* (*43*) to derive the critical N deposition rates to limit terrestrial biodiversity loss for different biomes in the GLOBIOM model (table S5). The critical N deposition rates to limit terrestrial biodiversity loss are based on (*84*),

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which presented an extensive synthesis of empirical studies (*94*). Forest and grassland, which are spatially represented in the GLOBIOM model for both historical years and future projections, are divided into eight biomes based on the climate zones from the Köppen-Geiger climate classification (*95*). Forest and grassland areas with N load exceedance are obtained by overlaying the spatially explicit nitrogen deposition projections by GEOS-Chem, biome maps projected by the GLOBIOM model, and the biome-specific critical N deposition rates.

Uncertainty analyses

Our analyses include several uncertainties. First, the evaluation of future disease burdens associated with air pollution uses grid level (2° latitude by 2.5° longitude) population structure and baseline mortality rates from the year 2015 due to a lack of their projections at fine geographical resolution for the future. This may lead to a moderate underestimation in health benefits of nitrogen interventions because current literature indicates that aging may increase the share of populations vulnerable to air pollution–related premature deaths (*41*, *96*).

Second, we used the premature mortalities metric for evaluating public health impacts of air pollution in present-year and future scenarios, which is a widely used metric by the Global Burden of Disease study (*19*) and air quality studies (*18*). However, another metric, years of life lost (YLL), incorporates both the concept of premature deaths and losses of life years from standard life expectancy at age of death; it thus comprehensively represents losses of human welfare from air pollution exposure. However, for a lack of future predictions of standard life expectancy for all countries under various future SSPs and for ease of interpretation of drivers of future public health burdens (nitrogen policies, populations growth, etc), we use the premature death metric here. When more data become available in the near future, the YLL metric could be used for more compressive prediction of future disease burdens and their differences across countries.

Third, our projected future agricultural NH_3 emissions from GLOBIOM with a nitrogen budgeting module well represent influences of socioeconomic development and climate policies on land use, detailed agricultural production. and management. However, it currently excludes the impact of climate change on NH_3 emission factors. Under a warmer climate with more extreme precipitation, fertilizers evaporate or leach N_r quicker, and more sophisticated technological combinations are needed to help maintain a high NUE. Still, this remains a methodological development limitation since, currently, there does not exist a model that simultaneously and endogenously represents the influences of agricultural production, supply, trade, and climate on NH_3 emissions. Process-based models such as flow of agricultural nitrogen model represent climate impacts on NH_3 emissions but have to use prescribed agricultural activity levels (*97*).

Fourth, recent research shows that airborne aerosols can affect crop yields via both direct and diffused radiation (*98*). We were not able to represent crop benefits of $PM_{2.5}$ mitigation because GEOS-Chem does not simulate aerosol-radiation feedback. Inclusion of joint benefits of ozone and $PM_{2.5}$ reductions may lead to larger yield savings.

Fifth, nitrogen deposition provides a source of nitrogen input to global cropland, and such inputs could be critical to nitrogen fertilizer–scarce regions such as Africa. Impacts of reduced nitrogen deposition on crop yields could be evaluated, in future studies, using crop yield response curves to total N inputs (*49*, *50*). Such effects are not evaluated here because GLOBIOM uses a nitrogen budget approach to ensure that sufficient nutrients are applied to ensure crop and pasture production. The crop and pasture production (harvested biomass withdrawal) is endogenously estimated by the IAM as a result of projected future demand and market dynamics. The harvested biomass is multiplied with N contents for which different assumptions are made in the three IAMs. On the basis of withdrawals and assumptions of the exogenous scenarios for the NUE following Kanter *et al.* (*35*), the GLOBIOM estimate the nutrient requirements of the crops. In the scenarios, the available organic fertilizers (i.e., manure), atmospheric deposition, and symbiotic and nonsymbiotic N fixations are subtracted from the nutrient requirements to estimate the need for inorganic fertilizers. Therefore, the nutrient requirements of the crops are always met in the nitrogen budget simulated by the GLOBIOM.

Last, we do not focus on individual technologies but bulk sectoral interventions as INMS scenarios represent. Moreover, we call these interventions "aspirational" as to some extent, they represent the best case combing demand- and supply-side management strategies and technologies while recognizing that substantial socioeconomic and political barriers exist, and only removing them could make these aspirational interventions become fully achievable and feasible. For example, regulating ammonia emissions in the U.S. or taking away fertilizer subsidies in India may not be politically feasible for the foreseeable future. The goal of 70% crop system NUE in the high-ambition nitrogen policy future scenario can be very difficult for fruits and vegetables, even with good adoption of best management practices for those cropping systems. Technologies such as nitrification inhibitors have shown considerable promise in some, but not all, circumstances, and even when they are adopted, farmers do not necessarily reduce their application rates of N fertilizers. However, analyzing aspirational nitrogen interventions and comprehensively evaluating consequent benefits for human, crop, and ecosystem health are critical for incentivizing integrated nitrogen management policies and sustainable development.

Supplementary Materials

This PDF file includes:
Figs. S1 to S18
Tables S1 to S5

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