Halving global ammonia emissions with cost-effective measures

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Xiuming Zhang [1,2,3], Yi Sun[4], Yujing Gao [1,5], Chen Wang [1,2], Xia Liang [6], Shu Kee Lam [6], Shaohui Zhang[3], Wilfried Winiwarter[3,7], Hans J. M. van Grinsven [8], Mark A. Sutton [9], Deli Chen [6] & Baojing Gu [1,2,10] ✉

Excess ammonia (NH_3) emissions from human activities pose severe threats to global ecosystems and human health. Although urgent control of NH_3 emissions is needed, a comprehensive quantification of mitigation strategies and their cost-effectiveness is lacking on a global scale. Here we employ a multi-model framework to evaluate 32 mitigation measures across 7 sectors in 185 countries. Our analysis reveals that strategic implementation of technological and non-technological (policy and behavioural) measures could reduce global NH_3 emissions by up to 60% at an average cost of US$7.4 per kilogram of NH_3. The estimated implementation cost of US$274 ± 116 billion is far outweighed by the resulting environmental, health and resource benefits, which we indicatively estimate at US$722 ± 302 billion. Priority action in China and India could yield the largest net gains, whereas Sub-Saharan Africa faces limited cost-effectiveness owing to structural and economic barriers. Future scenarios indicate that ambitious implementation pathways could halve NH_3 emissions by 2050, whereas weak climate action and inadequate nitrogen regulations would drive continued emission growth, leading to substantial environmental deterioration. These findings highlight both the feasibility and urgency of integrating NH_3 control into multi-objective policies for food security, air quality and sustainable development.

Ammonia (NH_3), a colourless and pungent gas, plays an intrinsic role in Earth's nitrogen cycle and is vital for agricultural productivity, especially in fertilizer synthesis[1]. Over the past four decades, there has been a marked increase in global NH_3 emissions, driven largely by the growing demand for agricultural products and changes in dietary preferences[2]. Large countries with important agricultural sectors, such as China, India and the United States, are key contributors to this rise[3]. Concurrently, the adverse effects of NH_3 emissions on human health and ecosystems have become a growing concern. Ammonia

contributes to the formation of fine particulate matter in the atmosphere, leading to cardiovascular and respiratory diseases in humans[4]. It also causes biodiversity loss in terrestrial and aquatic ecosystems through eutrophication, acidification and changes in plant community structures, disrupting the ecological balance[1].

Despite the well-documented environmental and health impacts of ammonia, the development and implementation of targeted NH_3 mitigation policies remain at an early stage globally, with most actions to date limited to high-level commitments or indirect regulatory

[1]State Key Laboratory of Soil Pollution Control and Safety, Zhejiang University, Hangzhou, China. [2]College of Environmental and Resource Sciences, Zhejiang University, Hangzhou, China. [3]International Institute for Applied Systems Analysis, Schlossplatz 1, Laxenburg, Austria. [4]City Brain Institute, Hangzhou City University, Hangzhou, China. [5]Appalachian Laboratory, University of Maryland Center for Environmental Science, Frostburg, MD, USA. [6]School of Agriculture, Food and Ecosystem Sciences, The University of Melbourne, Victoria, Australia. [7]Institute of Environmental Engineering, University of Zielona Góra, Licealna 9, Zielona Góra, Poland. [8]PBL Netherlands Environmental Assessment Agency, The Hague, the Netherlands. [9]UK Centre for Ecology and Hydrology, Edinburgh Research Station, Bush Estate, Penicuik, Midlothian, UK. [10]Zhejiang Provincial Key Laboratory of Agricultural Resources and Environment, Zhejiang University, Hangzhou, China. ✉e-mail: bjgu@zju.edu.cn

measures. For example, the Colombo Declaration on Sustainable Nitrogen Management (2019) represents a voluntary international commitment to halve nitrogen waste[5], and regional actions such as the EU's National Emission Ceilings (NEC) Directive[6] and China's enhanced fertilizer controls under its 14th Five-Year Plan signal emerging policy traction[7]. However, comprehensive and enforceable NH_3-specific regulations remain limited in most countries. Current research and initiatives mainly target agricultural emissions, which is consistent with the dominant role of the agricultural sector, yet other sectors such as waste management, household activities, industry and transportation also require consideration[8]. The costs of implementing various abatement measures and their benefits for environmental and human health remain poorly understood on a global scale[9], hampering understanding and informing policy for comprehensive NH_3 mitigation strategies. An integrated analysis assessing the costs and benefits of mitigation strategies in various regions, considering their unique socioeconomic and environmental contexts, is urgently needed to guide effective and efficient global NH_3 mitigation policies.

To address this knowledge gap, this study assesses the mitigation potential, costs and benefits of various NH_3 mitigation strategies at global and regional scales. Employing a multi-model coupled assessment framework (Extended Data Fig. 1), we evaluate 32 mitigation measures across 7 sectors in 185 countries (Supplementary Table 1) to identify cost-effective strategies that deliver net benefits for society. The study quantifies the global NH_3 mitigation potential through the combined implementation of selected measures, pinpointing major sources and priority regions for reduction. It also examines marginal abatement cost curves (MACC) for NH_3 emissions in different countries/regions to determine the most favourable measures for each. Finally, the study analyses the various NH_3 mitigation ambitions, together with their social costs and benefits under mid-term based on scenarios using the Shared Socioeconomic Pathways–Representative Concentration Pathways (SSP–RCP) framework[10,11] for 2020–2050 to provide a comprehensive understanding of potential policy impacts.

Global NH₃ emissions

Over the past four decades, global NH_3 emissions increased by approximately 48%, rising from 42 ± 3 teragrams (Tg) in 1980 to 62 ± 6 Tg in 2020, as illustrated in Fig. 1a. This increase is primarily attributed to rising food demand, which has driven growth in agricultural emissions, particularly from cropland fertilization and livestock manure management[2]. Cropland emissions increased from 14 ± 2 Tg NH_3 to 22 ± 2 Tg NH_3, and livestock emissions rose from 11 ± 1 Tg to 16 ± 2 Tg. The waste sector, which includes emissions from human solid waste and wastewater management, contributed 2–4 Tg NH_3 emissions globally. The household sector maintained a steady increasing trend of NH_3 emission, reaching 2 Tg NH_3 in 2020, predominantly from human excretion, cooking and heating. NH_3 emissions from the industrial, power and transport sectors, typically linked with combustion processes[3,12], collectively account for 4–5% of total NH_3 annually. These non-agricultural emissions, previously underestimated in global assessments[13], demonstrate the diverse sources of NH_3 emissions. Emissions from biomass burning such as forest fires, savanna and grassland fires, are categorized under 'other sectors', which represent ~3–4% of the total NH_3 emissions. Emissions from wildlife, wetland and oceans are not included in this analysis due to insufficient global data and inadequate evaluation methods.

Figure 1b demonstrates that China and India are the primary contributors to global NH_3 emissions, jointly accounting for over a third of the total. This high level of emissions can be attributed to their large populations and extensive agricultural activities, with fertilizer use in croplands being the dominant source in China and livestock-related emissions contributing more prominently in India[2]. Other Asian countries (OA) collectively contribute 16 ± 3%, signifying their substantial role. Sub-Saharan Africa (SSA), with a growing share, contributed 13 ± 2% in 2020, whereas Europe and North America (NA) act as notable

emitters with their total contributions of 14 ± 3% (9 ± 1 Tg) NH_3 emissions. Latin America (LA), including Brazil, accounts for 7 ± 1 Tg NH_3 per year. The Middle East and North Africa (MENA), along with the Former Soviet Union (FSU) exhibit moderate contributions. Oceania has the lowest emission level of 1 ± 0.5 Tg NH_3 per year, which could be attributed to the region's smaller population and less intensive agricultural practices[14].

The spatial distribution of NH_3 emissions from 1980 to 2020 reveals distinct regional trends, with a notable increase in many parts of the world (Fig. 1c,d). This upward trajectory is driven primarily by anthropogenic activities, particularly the expansion of intensified agricultural practices to sustain a burgeoning global population, coupled with the widespread adoption of synthetic nitrogen fertilizers (for example, urea-based formulations)[15]. The major NH_3 emission hotspots[16] are located in East Asia (China), South Asia (India/Pakistan), the central US and parts of Europe, where they are characterized by intensive agricultural production, especially high livestock densities and heavy fertilizer application, rather than necessarily by high population density.

Abatement cost and benefits across sectors

To evaluate the global and regional NH_3 mitigation potential and associated costs, this study integrated 32 mitigation measures across seven sectors (Extended Data Fig. 2) into CHANS and GAINS models. Global MACCs covering all 32 NH_3 mitigation measures are illustrated in Fig. 2a. Options are ranked by increasing marginal cost, from low-cost measures such as dietary shifts, improved crop and soil management, 4 R fertilization and low-emission manure application, to higher-cost interventions such as NH_3 scrubbers, NH_3 slip catalysts and the development of low-NH_3 alternative goods. However, the implementation feasibility of these options depends on local agronomic capacity, advisory services and farmers' economic risk tolerance.

The curve shows a wide cost range, with the global all-sector average marginal cost estimated at US$7.4 per kilogram of NH_3, and a total technical mitigation potential reaching 60% of global anthropogenic NH_3 emissions. In general, technological measures dominate both the mitigation volume and cost, accounting for 28 Tg NH_3 abatement at a cost of US$205 billion (Fig. 2b). Behavioural options, although essential for demand-side engagement, such as dietary shifts and waste reduction, offer an important mitigation contribution (9 Tg NH_3) at a cost of US$68 billion. From a policy perspective, about one-third of total mitigation (28 Tg NH_3) is delivered by measures explicitly targeting NH_3 emissions (for example, manure management and fertilizer formulation), whereas the remainder (10 Tg NH_3) comes from broader strategies that primarily target other environmental goals (for example, greenhouse gas (GHG) reduction and nutrient recycling) but also yield NH_3 abatement as a co-benefit[17].

Regional heterogeneity in MACCs is highlighted in Fig. 2c and detailed in Supplementary Figs. 3–13. Regions with stronger agricultural emissions and mitigation potential, such as India and China, show larger abatement potential at lower costs, whereas structurally constrained regions such as Sub-Saharan Africa face steeper marginal costs due to limited mitigation readiness. The curvature and slope of each regional MACC (Fig. 2d) reflect not only economic conditions but also the underlying structure of emissions and the availability of low-cost mitigation levers.

Figure 3a shows that India emerges with the lowest unit abatement costs (UAC) at US$4.8 per kilogram of NH_3, which is primarily due to the large abatement potential (5.8 Tg), widespread opportunities to improve nitrogen use efficiency and relatively low implementation costs. Europe, with a smaller abatement amount (3.3 Tg), also achieves a low UAC at US$5.4 per kilogram of NH_3 through mature regulatory systems and optimized farming practices. China contributes the largest abatement volume (8.1 Tg), driving the highest total mitigation cost (US$51 billion), and its UAC remains moderate owing to ongoing
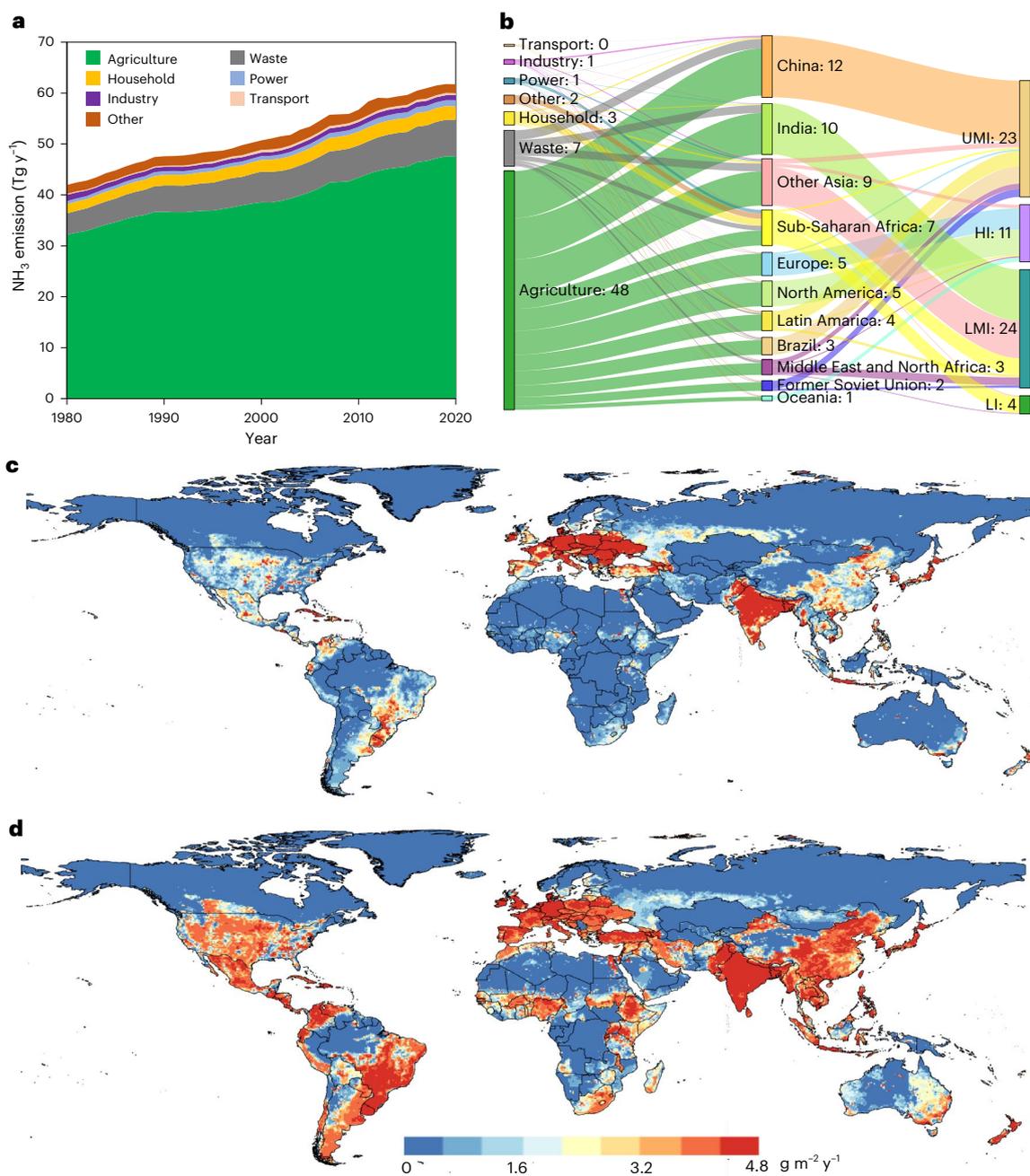
Fig. 1 | Global NH₃ emissions from 1980 to 2020. a, NH$_3$ emissions by sector during 1980–2020. **b**, NH$_3$ emission flows among sector, region and income group in 2020. **c,d**, spatial patterns of NH$_3$ emission density in 1980 (**c**) and 2020 (**d**). Detailed country classification can be found in Supplementary Table 1. Maps were created based on the integration of CHANS emission inventory and EDGAR annual grid maps with 0.5 × 0.5 degree resolution. UMI, upper-middle income; LMI, lower-middle income; HI, high income; LI, low income. Basemaps in **c** and **d** are sourced from GADM (https://gadm.org/).

modernization in agriculture and waste management. By contrast, SSA faces the highest UAC at US$14 per kilogram of NH$_3$, not because of high baseline agricultural emissions, which remain low owing to limited input use, but due to structural challenges. These include fragmented farming systems, poor infrastructure and limited access to capital and technology. The region requires substantial upfront investments in basic infrastructure and training to enable effective implementation of mitigation measures.

The global total implementation cost for the proposed NH$_3$ mitigation options is estimated at US$274 ± 116 billion, based on 2020 technology and price levels. The mitigation potential and associated costs vary significantly across different sectors, as shown in Fig. 3. The agricultural

sector, encompassing both cropland fertilization and livestock management, offers the largest direct technological mitigation potential, with 23 Tg NH$_3$, abated at a low average cost of US$2.6 per kilogram (Fig. 3a), accounting for 61% of the total mitigation potential while contributing only 21% of the total cost. The household sector, primarily through behavioural measures such as dietary shifts and food waste reduction, contributes a substantial 8.2 Tg of NH$_3$ abatement, despite its low baseline emissions (2.7 Tg), and incurs a moderately higher cost of US$3.6 per kilogram, reflecting the systemic nature of behavioural change. Similarly, the waste sector (solid waste and wastewater) contributes 3.6 Tg of abatement at a cost of US$13.8 per kilogram of NH$_3$, due to the infrastructure and operational investments required for
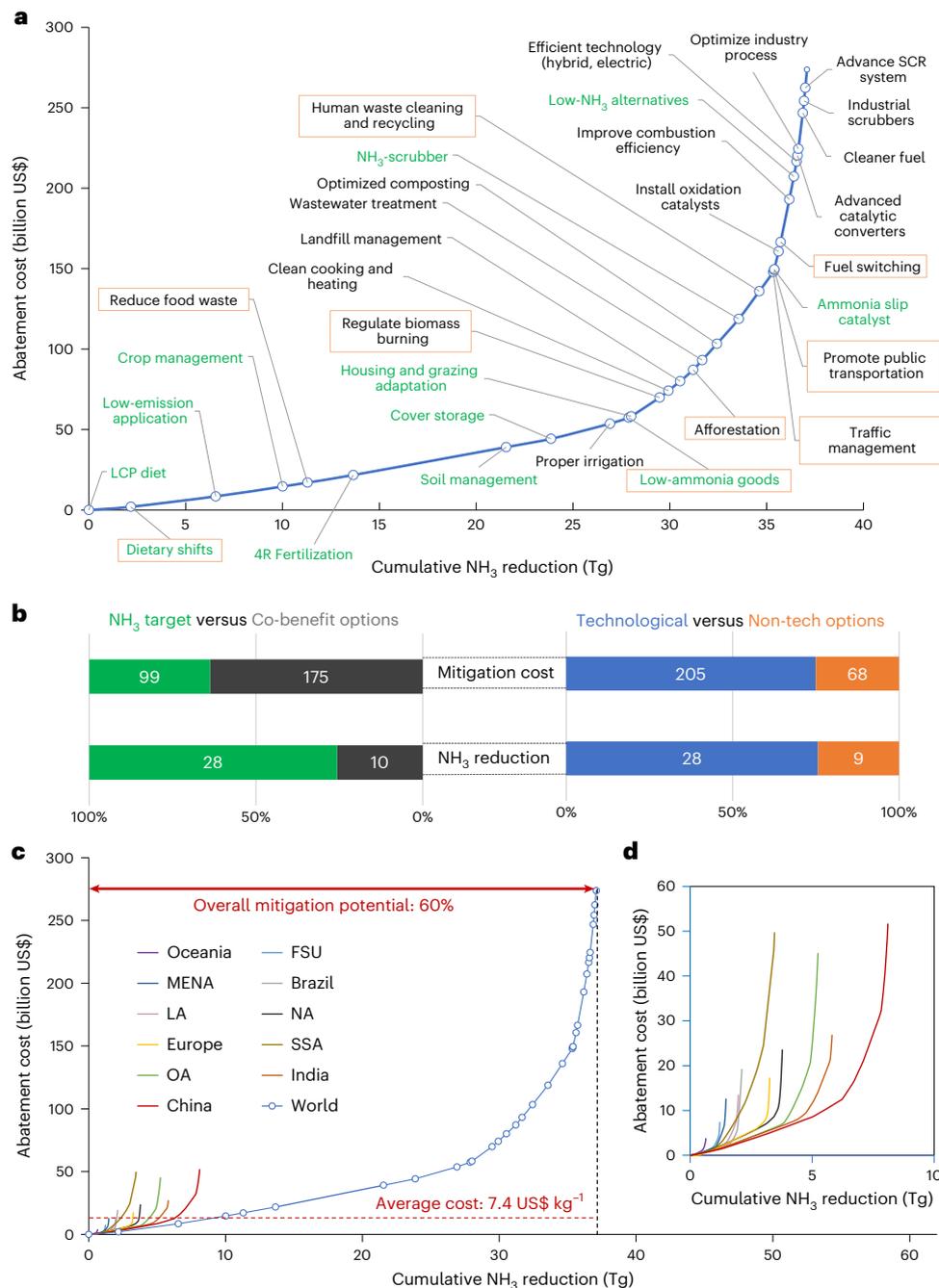
Fig. 2 | MACC of global NH$_3$ emissions. a, MACC of global NH$_3$ emissions by option, the x axis stands for the value of cumulative NH$_3$ mitigation and the y axis is the marginal abatement cost of the mitigation option in dollars per kilogram of NH$_3$ mitigated. Note that the values do not include the financial value of N saved by reduced NH$_3$ emissions of the measures listed; each dot on the MACCs represents a different mitigation option, and all options are ranked according to their unit costs, with the least costly on the left. Options labelled in green represent NH$_3$-targeted options, whereas options with orange borders are behavioural options; the remaining options are non-technological options and/or co-benefit options. Detailed option classification and description could

be found in Supplementary Tables 3–5. **b**, NH$_3$ mitigation potential and costs categorized by NH$_3$-targeted versus co-benefit options and technological versus non-technological options. **c**, Global and regional NH$_3$ mitigation potential and cumulative cost. 60% represent the overall NH$_3$ mitigation potential globally under the current baseline. The red dashed line represents the global average abatement cost (dollars per kilogram of NH$_3$ abated), which is calculated by dividing the global total mitigation cost by the total NH$_3$ reduction. **d**, The enlarged version of regional MACC in **c** for better visibility. LCP, low-crude protein; 4R, right time, right type, right rate and right place of fertilization; EENF, enhanced efficiency nitrogen fertilizer; SCR, selective catalytic reduction.

source separation, composting and advanced treatment. The power and industry sectors exhibit limited abatement potential (0.9 Tg and 0.7 Tg NH$_3$, respectively), but incur high marginal costs of US$66 and US$78 per kilogram, respectively (Fig. 3a), and they together contribute only 4% of the total mitigation volume while absorbing over 40% of total mitigation costs. The transport sector shows the highest unit

cost (US$80 per kilogram) with minimal abatement potential (0.2 Tg), largely due to the limited role of NH$_3$ in modern vehicular emissions and the high cost of emission control technologies such as NH$_3$ slip catalysts. The 'other' sector, which includes biomass burning emissions, offers moderate potential (0.9 Tg) at relatively low cost (US$10 per kilogram), but faces higher uncertainty due to diffuse sources.
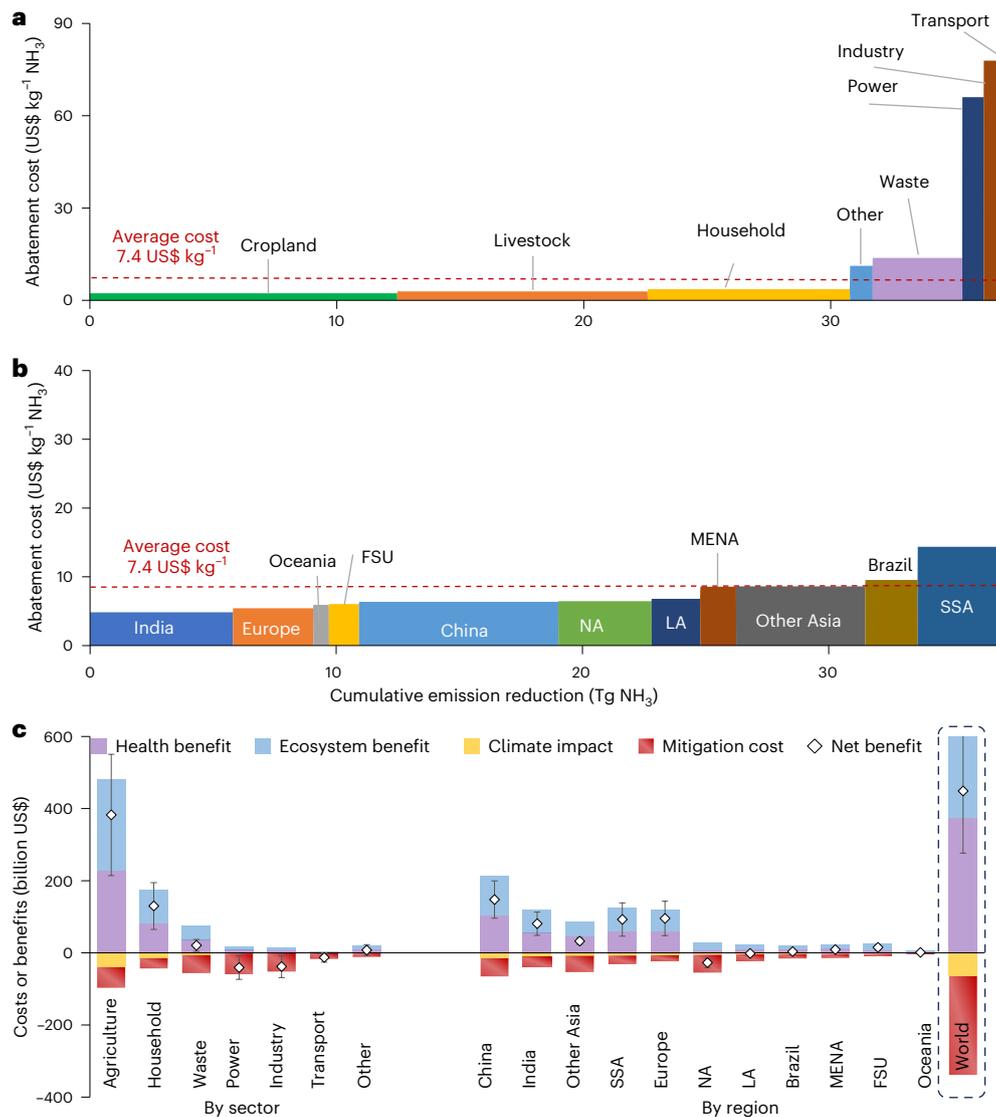
Fig. 3 | NH₃ mitigation costs and benefits by region and sector. a, Sectoral contributions and marginal costs of global NH₃ mitigation. **b,** Regional contributions and marginal costs of global NH₃ mitigation. **c,** Cost and benefit distribution of NH₃ mitigation by sector and region for the baseline year 2020. Net benefits are presented as white diamonds (means) ± 95% confidence intervals, based on the standard errors of 1,000 Monte Carlo simulations.

Cost-effectiveness across region and sector

NH₃ mitigation potential and costs exhibit pronounced regional disparities (Fig. 3b). Oceania shows the lowest level of mitigation and associated costs, in line with its relatively minor emissions and limited scope for NH₃ abatement. India and China, with a combined mitigation potential of 14 Tg NH₃ emissions, can achieve substantial reductions at costs below the global average, underscoring their future pivotal role in global NH₃ mitigation efforts, as shown in Fig. 3b. FSU demonstrates the limited potential of 1.0 Tg NH₃ reduction with the total cost of US$7.8 billion. Europe and NA share similar NH₃ mitigation potential (~3–4 Tg), with corresponding costs of US$18 billion and US$24 billion, respectively. MENA, LA and Brazil present higher implementation costs to achieve their NH₃ mitigation potentials. Notably, OA and SSA hold a considerable NH₃ mitigation share but much higher implementation costs than the global average. The comprehensive execution of NH₃ mitigation options in SSA will require a substantial investment of US$57 billion, primarily for enhancements in the waste, power and industry sectors, able to achieve 3.5 Tg NH₃ abatement.

Although NH₃ mitigation in various regions involves substantial costs, the associated societal benefits, particularly in preventing premature human mortality and ecosystem degradation, are considerable (Fig. 3c). The monetized costs of premature mortality and ecosystem degradation were estimated using region-specific unit damage costs derived from published literature, primarily based on willingness-to-pay methods for ecosystem services and the economic valuation of health impacts from PM₂.₅ exposure, scaled by population, gross domestic product (GDP) per capita and NH₃ emission density (see details in Methods). China leads with the highest net benefits of US$148 ± 57 billion, followed by Europe, NA and India with benefits of US$95 ± 39 billion, US$92 ± 39 billion and US$81 ± 33 billion, respectively (Fig. 3c). The high values in these regions stem from a combination of elevated ambient concentrations, large exposed populations and underlying health conditions. By contrast, OA, FSU and MENA present lower net benefits, indicating a less cost-effective outcome. SSA faces the most challenging cost–benefit outlook, where the estimated mitigation cost (US$57 ± 23 billion) exceeds the total monetized benefits (US$23 ± 11 billion). This imbalance mainly stems from our cost–benefit analysis being conducted from all-sector NH₃ control perspective, without fully accounting for the broader GHG, air quality or long-term ecosystem synergies. Importantly, the regional average
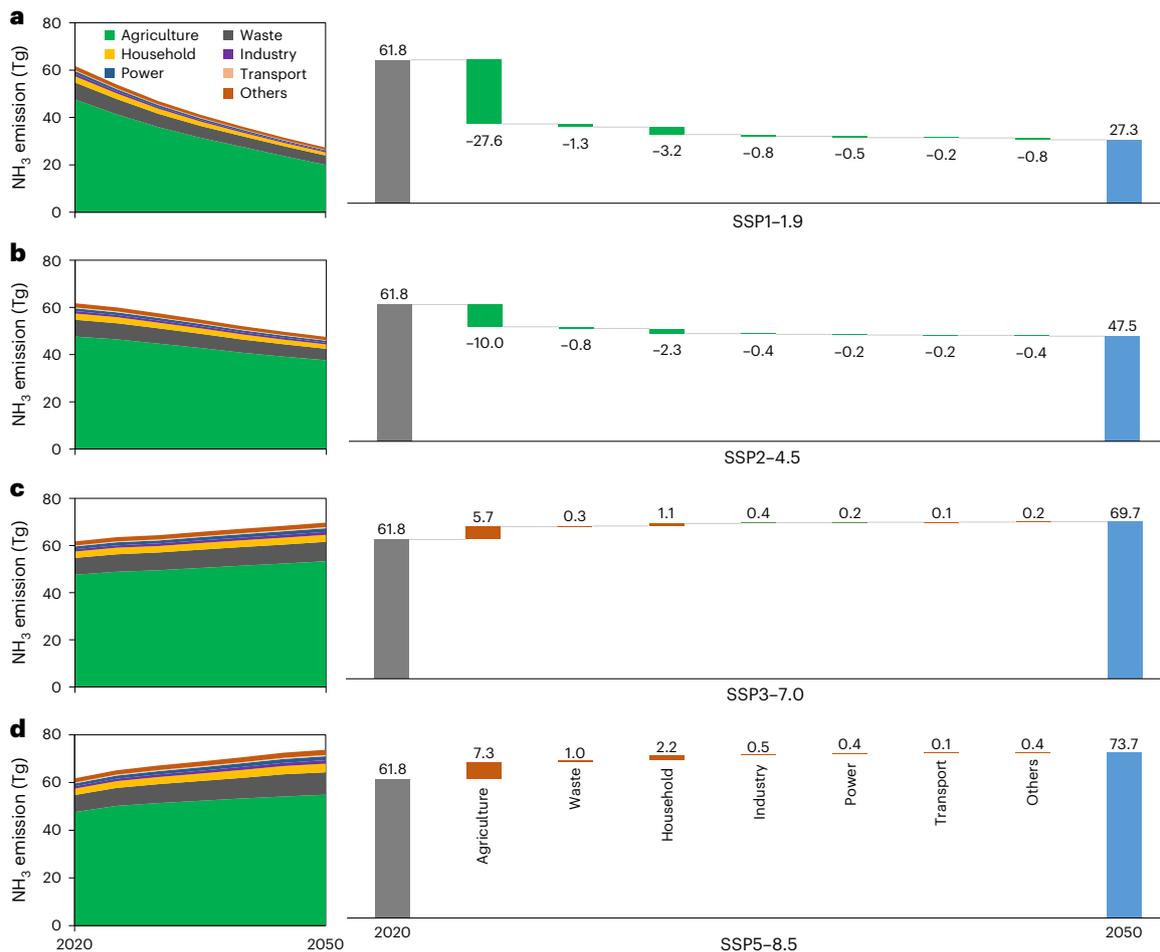
Fig. 4 | Projected global NH₃ emissions by sector from 2020 to 2050 under representative SSP–RCP scenarios. a–d, NH₃ emission trajectories and sectorial emission changes from 2020 to 2050 under SSP1–1.9 (**a**), SSP2–4.5 (**b**), SSP3–7.0 (**c**) and SSP5–8.5 (**d**).

masks opportunities for selectively implementing cost-effective measures, particularly in agriculture and sanitation, where abatement can generate local health and productivity cobenefits.

The total estimated benefits from global NH₃ mitigation amount to US$722 ± 302 billion, comprising US$373 ± 148 billion in health benefits[4] and US$414 ± 183 billion in ecosystem benefits[18], offset by US$65 ± 29 billion in negative climate impacts[19]. The agricultural sector presents the most favourable benefit–cost ratio (BCR) at 7.6 with US$58 ± 23 billion in mitigation costs but US$440 ± 177 billion in total benefits from health, ecosystem and climate impacts (Fig. 3c). This accounts for 61% of the total estimated benefits, resulting in a net benefit of US$382 ± 155 billion from agriculture. The waste sector, with costs at US$50 ± 18 billion and total benefits at US$71 ± 27 billion, shows a BCR of 1.5, suggesting a relatively cost-effective mitigation. The household sector has estimated benefits of US$42 ± 15 billion compared with mitigation costs of US$33 ± 10 billion, yielding a BCR of 1.4. Conversely, the transport, industry and power sectors encounter low BCRs at -0.2 – 0.5 for NH₃ mitigation, which underscores the economic challenges of reducing NH₃ emissions in these sectors unless the considerable cobenefits of reducing GHGs and air pollutants (NO$_x$, SO₂ and PM$_{2.5}$) are factored in[20].

Future pathways

To evaluate future NH₃ emission trajectories, four distinct SSP–RCP scenario analyses (Methods) spanning 2020–2050 were conducted. The SSP1–1.9 scenario, characterized as the 'sustainability' pathway (Extended Data Table 1), demonstrates a substantial reduction in NH₃

emissions, with a decrease of 34.0 Tg between 2020 and 2050, representing a reduction of more than 50% (Fig. 4a and Extended Data Fig. 3). This decrease is mainly driven by sustainable diets, reduced food waste and resource-efficient production systems, with notable 27.6 Tg and 3.2 Tg reductions in the agriculture and waste sectors, respectively. In this scenario, all regions show a downward emission trend from 2020 to 2050, albeit at different rates, as depicted in Fig. 5a. In addition, prescribed burning practices are included in the other sector under SSP1–1.9, helping to mitigate wildfire risks, particularly in fire-prone regions.

The SSP2–4.5 scenario, known as the 'stabilization' pathway, features intermediate levels of climate mitigation efforts and has moderate ambition on NH₃ mitigation (Fig. 4b). This scenario envisions a trajectory balancing economic growth with environmental sustainability. Although SSP2–4.5 does not aim as ambitiously as SSP1–1.9, it includes measures to stabilize and gradually lower NH₃ emissions across key sectors, including agriculture (−10 Tg), waste management (−2.3 Tg), household practices (−0.8 Tg) and fuel combustion-related sectors (−0.8 Tg). Most regions under SSP2–4.5 exhibit a steady but less significant decrease in emissions compared with SSP1–1.9, whereas SSA shows a slight rise by 2050 (Fig. 5a), driven by rising population and intensified food demand.

In the SSP3–7.0 scenario of the 'regional rivalry' world, NH₃ emission-reduction actions in different countries and regions lack effective targets and technology development. Major emitting countries progress slowly on NH₃ emission-reduction policies, and a noticeable upward trajectory in NH₃ emissions is projected by 2050 (Fig. 4c). The agricultural sector alone contributes an increase of 7.3 Tg, driven
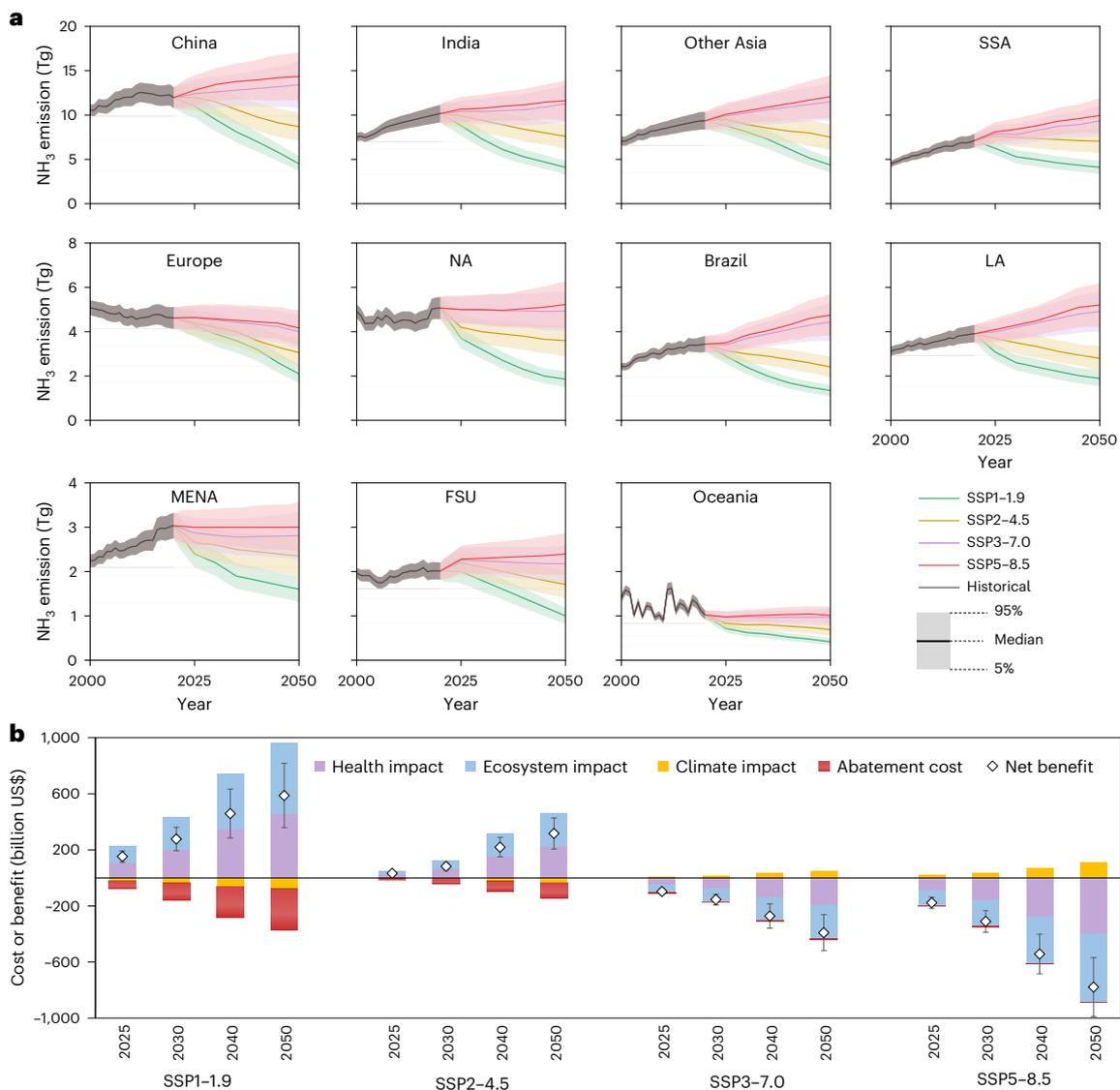
Fig. 5 | Regional NH₃ emissions and cost-benefits under representative SSP-RCP scenarios. a, Projected regional NH₃ emission trajectories under SSP1–1.9, SSP2–4.5, SSP3–7.0 and SSP5–8.5. Shaded bands indicate the 95% confidence interval of estimated NH₃ emissions. **b**, Global costs and benefits of NH₃ emissions and mitigation from 2025 to 2050 by scenario. Net benefits are presented as white diamonds (means) ± 95% confidence intervals, based on the standard errors of 1,000 Monte Carlo simulations.

by inefficient fertilizer use, expansion of livestock systems and lack of policy enforcement. Only Europe presents a slight decrease in NH₃ emissions (Fig. 5a).

SSP5–8.5 represents a world with fossil-fuel-intensive economic growth and high energy demand, with little attention to controlling NH₃ emissions. Under this pathway, NH₃ emissions rise to 73.7 Tg by 2050 (Fig. 4d). Agriculture drives most of this increase, as production is intensified through greater fertilizer use and livestock density, with limited regard for environmental impacts. Emissions from waste and households increase by 2.2 Tg and 0.9 Tg, respectively, reflecting weak investment in treatment infrastructure and rising consumption. Industry, power and transport add another 1.0 Tg due to minimal deployment of abatement technologies. The 'other' sector also contributes substantially, mainly because of more frequent and severe wildfires.

Globally, SSP1–1.9 requires substantial abatement costs (US\$296 ± 92 billion), but the benefits for health, ecosystems and climate rise to US\$884 ± 292 billion by 2050 (Fig. 5b), demonstrating the long-term economic payoff of strong sustainability action. Under SSP2–4.5, moderate costs (US\$111 ± 33 billion) still yield growing net

benefits, reaching US\$317 ± 129 billion by 2050. By contrast, SSP3–7.0, with weak and uneven NH₃ control, leads to worsening health and ecosystem damage valued at US\$390 ± 198 billion. SSP5–8.5, marked by minimal NH₃ abatement and fossil-fuel-intensive growth, drives even larger losses (US\$778 ± 435 billion), underscoring the cost of inaction.

In general, across mitigation pathways (SSP1–1.9 and SSP2–4.5), most regions gain net benefits (Extended Data Figs. 3–5), with China showing the largest gains (Extended Data Fig. 6). Conversely, under non-mitigation pathways (SSP3–7.0 and SSP5–8.5), nearly all regions, except Europe, suffer increasing health and economic losses (Extended Data Fig. 6). Agriculture remains the central source of NH₃ emissions and the main target for mitigation (Extended Data Fig. 7); in mitigation scenarios, its social benefits are large enough to offset the sector's damages under non-mitigation futures.

Policy implication

Our findings highlight the need for targeted and sector-specific strategies to achieve effective NH₃ mitigation, with agriculture and waste management emerging as global priorities. In the agricultural sector,
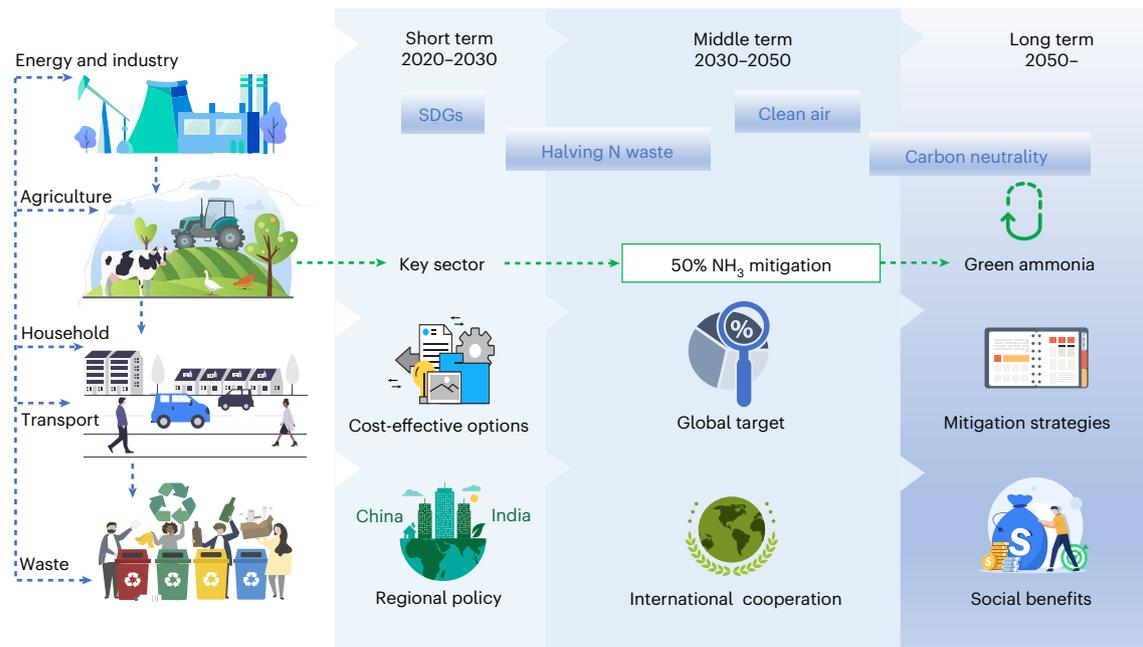
Fig. 6 | Roadmap for global NH₃ mitigation. A staged pathway to reduce global NH$_3$ emissions across all major source sectors: agriculture (dominant source), energy and industry, household, transport and waste. The roadmap links sector-specific strategies with international cooperation and cost-effective options that deliver social and environmental cobenefits. It defines coordinated global targets over three time horizons: short term (2020–2030), 20–30% reduction, driven by rapid adoption of proven, low-cost measures and clean air policies in key regions (for example, China and India); medium term (2030–2050), ~50% reduction, supported by broader structural transformation of agriculture and waste management, deployment of cleaner fuels and processes, and integration of NH$_3$ control into policies for food security, public health and sustainable development; long term (post-2050), >50% reduction, aligned with global goals on clean air, halving nitrogen waste, achieving carbon neutrality and advancing the SDGs. Icons from OfficePLUS Free Illustration Library under a Creative Commons licence CC0 1.0.

empirical evidence from regions such as Europe[21], China[22], Australia[14], the USA and Canada[23], confirms the effectiveness and practicality of abatement measures, not only for reducing NH$_3$ emissions but also for curbing nitrogen runoff/leaching and GHG emissions[24]. Successful practices include fertilizer use regulations, adoption of precision agriculture and financial support for low-emission manure systems and feed additives[25,26]. Nevertheless, strategies must balance reduced fertilizer use with food security concerns for key crops (rice, wheat and maize). In waste management, stricter standards for incineration, composting[27] and landfills can substantially cut NH$_3$ emissions, although these improvements often require high investment, especially in low-income regions. In the industry, power and transportation sectors, NH$_3$ abatement costs are high when calculated only from the perspective of NH$_3$. However, many of the evaluated measures are often implemented primarily for climate or air quality purposes, other than NH$_3$ control. These include transitioning to cleaner fuel, efficiency improvement and NO$_x$ control technologies in these sectors. In these cases, NH$_3$ abatement is best understood as a co-benefit rather than the main driver of intervention, which may nonetheless result in substantial cost savings when viewed from an integrated policy perspective. Mitigation choices must be sensitive to context, and policies should promote integrated approaches that account for both synergies and trade-offs among environmental, economic and welfare objectives.

Geographical differences shape NH$_3$ mitigation priorities. Asia, in particular China and India, accounts for the highest emissions and should lead global efforts, with cooperation among countries such as Pakistan, Indonesia and Bangladesh being crucial due to the transboundary nature of NH$_3$ pollution[28]. Europe, by contrast, is already experiencing a decline in NH$_3$ emissions; many effective NH$_3$ mitigation measures are enforced primarily through the EU Nitrate Directive[29], originally aimed at reducing water pollution. This reflects that NH$_3$ control could be effectively implemented when integrated with water and nutrient management frameworks, particularly in the agricultural sector. SSA faces a different problem: agricultural NH$_3$ emissions are projected to rise with growing fertilizer use and livestock production, and food security remains a priority[30]. The high cost of upgrading inadequate infrastructure makes NH$_3$ mitigation a formidable task in SSA. Considering the region's ongoing development in agriculture and low-income status, immediate NH$_3$ abatement is deemed a lower priority.

Despite the availability of effective NH$_3$ mitigation measures, implementation across sectors and regions faces multiple barriers, enablers and uncertainties. Economic constraints remain a major obstacle, particularly in low-income and middle-income countries where high upfront costs, for manure treatment, precision agriculture or waste infrastructure, restrict widespread adoption. Technological limitations, such as restricted access to advanced fertilizers and controlled-release formulations, along with institutional weaknesses such as fragmented policies or inadequate extension services, further hinder progress. Nevertheless, several important enablers can support wider uptake. These include strong cobenefits for climate mitigation (for example, GHG reductions), air and water quality improvement and enhanced agricultural productivity, especially when NH$_3$ control is embedded in multi-objective policies. Aligning NH$_3$ mitigation with global sustainable development agendas, such as the Colombo Declaration's goal to halve global nitrogen waste[31] and the United Nations Sustainable Development Goals (SDGs) (for example, SDG2 Zero Hunger, SDG6 Clean Water, SDG13 Climate Action and SDG15 Life on Land)[32], can enhance policy coherence and maximize environmental, social and economic gains. For example, the Europe Sustainable Development Report 2022[33] includes NH$_3$ emissions from agriculture as an SDG2 indicator, with a long-term goal to limit NH$_3$ emissions to 8 kg NH$_3$ ha^{-1}. Policymakers can further leverage these synergies by incorporating NH$_3$ abatement into national SDG strategies and air quality programmes. However, considerable uncertainties remain, including variability in behavioural adoption, the robustness of policy

enforcement and evolving technology costs, all of which underscore the need for flexible, context-specific approaches. A global roadmap (proposed in Fig. 6) and coordinated frameworks are essential for scaling action and addressing the transboundary nature of NH_3 pollution.

Uncertainty and limitations

Although our global NH_3 emission inventory has been cross validated using multiple independent sources, some uncertainties remain, as discussed in Supplementary Information Section 3. One notable limitation is the exclusion of NH_3 emissions from natural ecosystems, such as wetlands, oceans and wildlife owing to a lack of reliable data and robust evaluation methods. As a result, our analysis of NH_3 emission-reduction potentials and costs focused on major anthropogenic sectors and relies primarily on literature review combined with Coupled Human And Natural Systems (CHANS)[34] and greenhouse gas and air pollution interactions and synergies (GAINS)[35] simulations. The mitigation potential estimates should be interpreted as indicative technical–economic potential under modelled assumptions rather than guaranteed real-world performance.

Several limitations affect our cost–benefit projections. In particular, a sensitivity test shows that adoption rates and cost estimates are the primary sources of uncertainty in mitigation potential and cost-effectiveness, whereas assumptions on exposure–response functions dominate the uncertainty in health cobenefits (Supplementary Fig. 21). These findings highlight the importance of policy ambition, socioeconomic context and data quality in shaping model outcomes. Although our MACs reflect variation in socioeconomic capacity through per capita gross domestic product (PGDP)-adjusted costs and scenario-dependent adoption rates, we did not model dynamic changes in mitigation efficiency or the emergence of new technologies. In addition, structural inefficiencies, including fragmented supply chains, financing constraints and regulatory delays, may increase actual implementation costs beyond our reported uncertainty ranges. Future work could integrate technology diffusion models to better reflect innovation and learning effects across SSPs.

Regarding the valuation of NH_3-related impacts and mitigation benefits, coefficients and parameters used for quantification are derived from literature and model simulations (Supplementary Tables 3 and 4). Future damage cost coefficients have been adjusted to reflect changes in projected emission levels and socioeconomic development trajectories under each scenario. However, we acknowledge that this approach may introduce considerable uncertainty in assessing the broader social impacts of NH_3 reduction, particularly due to simplified assumptions about exposure–response relationships, ecological recovery dynamics and economic valuation of ecosystem services (see detailed discussion in Supplementary Information Section 4). Although we reported standard deviations for key metrics (for example, US$274 ± 116 billion for costs and US$722 ± 302 billion for benefits), these figures should be seen as indicative variability ranges rather than precise confidence intervals. Monte Carlo simulations account for parameter uncertainty but do not fully capture epistemic uncertainty related to structural assumptions, long-term behavioural responses and valuation methods. Consequently, our cost–benefit analysis should be viewed as a tool for assessing relative cost-effectiveness rather than a definitive statement of social desirability. Decisions on NH_3 mitigation are inherently complex and value driven, requiring careful consideration of ethical, institutional and cultural factors beyond simple economic metrics. In addition, our study does not systematically quantify the potential synergies and trade-offs between NH_3 mitigation and the control of other pollutants. Future research should prioritize multi-pollutant strategies that target simultaneous reductions in NH_3, GHGs and other air pollutants across region and sectors, thereby maximizing synergies, minimizing trade-offs and supporting broader goals such as carbon neutrality, clean air and the SDGs.

Methods

Global NH_3 emission inventory

This study compiled an updated global NH_3 emission inventory mainly based on the CHANS mass-balance model, with integration of credible global emission databases, including the Community Emissions Data System (CEDS)[36], Emission Database for Global Atmospheric Research (EDGAR)[37], Integrated Model to Assess the Global Environment (IMAGE)[38] and the Model of Agricultural Production and its Impact on the Environment (MAgPIE)[39] (Extended Data Fig. 1). Detailed descriptions of these NH_3 model datasets used in this study are provided in Supplementary Information Section 1. We also referred to regional (USA, UK and Australia) NH_3 emissions inventories and the published NH_3-related paper for national validation (Supplementary Fig. 18). Seven major sectors of NH_3 emissions are defined in this study for inventory compilation and source apportionment, including agriculture (fertilizer application, livestock manure and biomass burning), waste (solid waste management and wastewater treatment), household (cooking, heating and building), transport (on-road, rail and off-road), power (energy production and fossil fuel combustion), industry (explosives and acrylonitrile production) and others (biomass burning). Definitions for each emission source by sector are listed in Supplementary Table 2. The main data sources used in this study include the following.

(1) FAOSTAT[40], used for detailed crop production, land use and livestock population data. The World Bank[41], provided national-scale socioeconomic indicators such as human population and GDP. IFASTAT[42], supplied information on fertilizer consumption and nutrient use. Non-agricultural activity data such as fuel consumption are primarily based on IEA world energy balances[43]. Data on transportation activity, including vehicle counts and mileage, were sourced from the IEA Mobility Model[44]. Estimates of biomass burning area were derived from the Global Fire Emissions Database (GFED4s)[45] and MODIS satellite observations[46], whereas wastewater generation and treatment practices were informed by UNEP sanitation assessments[47], national environmental reports and peer-reviewed papers.

(2) Latest published papers on field experiments, meta-studies and national gas emission inventories that offer diverse parameters (for example, N content in crops, harvest index and manure recycling ratio) and regional-specific N_r emission factors (EFs) or global default values for countries that have not developed their own methods and EFs to enable the calculation of regional NH_3 emissions ($E_{NH_3,i}$) (equation (1),

$$E_{NH_3,i} = \sum_{j}^{185} \sum_{k}^{7} A_{i,j,k} \times EF_{i,j,k} \qquad (1)$$

where i, j, k represent the specific year, region and sector of NH_3 emissions, $A_{i,j,k}$ is the activity level data and $EF_{i,j,k}$ are the specific NH_3 emission factors, which were derived from a comprehensive literature review and from the emission models and datasets referenced in Supplementary Fig. 14.

Mitigation options and potential

To explore the overall NH_3 mitigation potential, we first conducted a literature review from the Web of Science published in 2000 to identify feasible NH_3 abatement measures by sector. Keywords used for the search included 'ammonia OR NH_3 emission OR ammonia emission inventory OR ammonia mitigation potential OR mitigation cost OR mitigation benefit', 'mitigation options OR abatement OR reduction', 'agriculture OR waste OR industry OR transport OR cropland OR livestock OR fertilizer' and 'cobenefits OR trade-offs'. The selection of

NH_3 abatement measures was guided by five main criteria: (1) high mitigation efficiency; (2) relatively low implementation cost based on available literature and international assessments; (3) broad applicability across sectors and geographies; (4) feasibility of regional implementation under current or projected socioeconomic conditions; and (5) the presence of clear cobenefits (for example, GHG reduction and air or water quality improvement) or recognized trade-offs. Based on the selection criteria and literature review, a total of 32 mitigation options across seven emission sectors were included in this study. These options were classified from different perspectives: that is, technological versus non-technological options, NH_3-targeted versus co-benefit options (Supplementary Fig. 2), to explore the feasibility and effectiveness of various mitigation strategies. A detailed description of each option's application scope, implementation cost, co-benefit or trade-offs is provided in Supplementary Tables 3–5. In general, the technological options primarily focus on equipment upgrades, process modifications and infrastructure improvements that require capital investment and technical implementation. By contrast, behavioural options emphasize changes in human activities that can be implemented through policy interventions and awareness campaigns. The NH_3-targeted options are specifically designed to reduce NH_3 emissions as their primary objective, whereas co-benefit options address other environmental concerns, such as reducing GHG emissions, improving air quality or enhancing resource efficiency while contributing to NH_3 mitigation. This classification framework allows a comprehensive assessment of the trade-offs between direct NH_3 reduction effectiveness and broader environmental benefits, providing policymakers with insights into optimal mitigation portfolio selection based on specific regional priorities and constraints.

Mitigation potentials of NH_3 emissions at the national scale were assessed by combining various mitigation options with the original emission inventory, which is calculated as in equation (2):

$$\Delta E_{NH_3,i,j} = \sum_k A_{i,k} \times EF_{i,k} \times \eta_{i,k,m} \times X_{i,k,m} \qquad (2)$$

where i, j, k represent the specific year, region and emission sector, $\Delta E_{NH_3,i}$ is the reduction potential of NH_3 emissions in year i, m represents a specific abatement option or the combination of multiple options, $\eta_{i,j,k,m}$ is the NH_3 abatement efficacy and $X_{i,j,k,m}$ is the implementation rate of the abatement technique or options.

Implementation costs
A technologically detailed bottom-up approach can assess the financial costs of implementing various NH_3 mitigation measures across nations/regions. Abatement options and their associated mitigation efficiency are characterized by major NH_3-emitting sectors such as agriculture, transportation, industry and waste management. The implementation cost of NH_3 emissions in this study is defined as a direct expenditure (the sum of investment costs and operation costs) for implementing measures to reduce NH_3 emissions from different emission factors, whereas the possible public costs (for example, subsidy to promote the control policy) are not considered. Here we mainly refer to the methodology of cost assessment from the GAINS model to calculate the abatement costs of implementing various NH_3 mitigation measures. The GAINS model has been widely used to determine least-cost abatement policies for reaching specified gas emission control targets in many countries and regions. The calculation of abatement costs is formulated in equation (3) as

$$AC_{i,k} = I_{i,k} \times \left[\frac{(1+r)^{lt_{i,k}} \times r}{(1+r)^{lt_{i,k}} - 1} \right] + FO_{i,k} + VO_{i,k} - FS_{i,k} \qquad (3)$$

where $AC_{i,k}$ represents the annual implementation cost, $I_{i,k}$ refers to the investment cost, r is the discount rate, $lt_{i,k}$ represents the lifetime of the

abatement technique (10–15 years), $FO_{i,k}$ is the fixed operating cost, $VO_{i,k}$ is the variable operating cost (for example, feed, gas, electricity, labour and water) and $FS_{i,k}$ represents saving costs from reduced use of N fertilizer. All cost data from the literature were adjusted by the purchasing power parity index and measured in constant 2017 US dollars by assuming 2% annual inflation. Detailed cost-calculation methods and parameters can be found in Supplementary Table 4. Country/regional differences in the mitigation cost were considered through a series of international cost indices (labour, non-energy materials, electricity, water and energy) to create a more heterogeneous representation of emissions and mitigation costs across countries. For non-traditional or emerging options where empirical validation is limited, we applied uncertainty bounds and conducted uncertainty analysis to capture the plausible cost range (Supplementary Table 2).

MACC
An MACC is an analytical tool used to understand the costs associated with emission reduction. Country-specific data on baseline emission sources, abatement potentials, capital and operating costs, and technology adoption rates allows estimation of regional-specific MACCs. Based on the efficiency of investigated mitigation options and annual implementation cost, we estimated the regional and global marginal abatement cost (MAC) of NH_3 mitigation to determine the additional cost associated with reducing one more unit of emissions. The basic equation for calculating the MAC is

$$MAC_m = \frac{\Delta C_m}{\Delta E_m} \qquad (4)$$

where ΔC_m is the cost change due to the implementation of the abatement measure m, and ΔE_m represents the corresponding change in NH_3 emissions.

Societal benefit assessment
Societal benefits ($SOC_{benefit}$) of NH_3 mitigation in this study are defined as the sum of benefits (avoided damage cost) for human health ($HH_{benefit}$), ecosystem service ($EH_{benefit}$) and climate impact (CL_{impact}), as shown in equation (5):

$$SOC_{benefit,i} = HH_{benefit,i} + EH_{benefit,i} + CL_{impact,i} \qquad (5)$$

The health benefit ($HH_{benefit,i}$) refers to the benefit of prevented mortality derived from $PM_{2.5}$ mitigation caused by NH_3 abatement[48]. We derived the baseline (2020) national-specific unit health damage costs ($Hcost_{2020,j}$) of NH_3 emission from the N-share methodology[4], which connected the economic cost of premature mortality per unit of NH_3 emission with the $PM_{2.5}$ concentration, population density, GDP per capita and total years of life lost. Then we estimated the changed health damage cost ($Hcost_{i,j}$) in a specific country and year based on the variation of regional NH_3 emission density and the PGDP, as shown in equation (6). The avoided health damage cost by NH_3 mitigation compared with 2020 is regarded as the health benefits, as presented in equation (7). It is noted that the estimated health benefits represent indicative magnitudes rather than precise valuations, given the uncertainties in exposure–response relationships, modelled chemical fractions of $PM_{2.5}$ and monetization based on PGDP-weighted approaches.

$$Hcost_{i,j} = Hcost_{2020,j} \times \sqrt[\alpha]{\frac{PGDP_{i,j}}{PGDP_{2020,j}}} \times \frac{Density_{i,j}}{Density_{2020,j}} \qquad (6)$$

$$HH_{benefit,i,j} = E_{2020,j} \times Hcost_{2020,j} - E_{i,j} \times Hcost_{i,j} \qquad (7)$$

where $E_{i,j}$ and $E_{2020,j}$ refer to the national NH_3 emissions in the years i and 2020, respectively (specific parameters provided in Supplementary

Table 7), $PGDP_{i,j}$ and $PGDP_{2020,j}$ refer to national GDP per capita in the years i and 2020, respectively, $Density_{i,j}$ and $Density_{2020,j}$ refer to NH_3 emission density in kilograms of NH_3 per hectare in the years i and 2020, respectively, and α is the coefficient for health damage cost, which is derived by correlation analysis between past NH_3 damage costs and PGDP and emission intensity.

Similarly, ecosystem benefits ($EH_{benefit}$) in this study are regarded as the avoided damage costs of the improvement of acidification and eutrophication of ecosystems due to NH_3 mitigation. We derived the baseline regional-specific unit NH_3 damage costs to the ecosystem ($Ecost_{2020,j}$) based on the willingness-to-pay method from European Nitrogen Assessment[49] and the latest peer-reviewed papers[21,50], which provided national damage cost estimation (specific parameters provided in Supplementary Table 7). Then we assessed the future changed ecosystem damage cost based on the changing NH_3 emission density and PGDP under the specific scenario to finally calculate the avoided ecosystem damage cost associated with NH_3 management (equations (8) and (9)). Please note that we acknowledge the inherent limitations and uncertainties associated with willingness-to-pay-based approaches. These include their dependence on socioeconomic context, valuation method (for example, contingent valuation versus revealed preference) and cultural perceptions of environmental and health risks. The precision of these estimates is not meant to represent exact national values, but to support comparative analyses of where mitigation may offer relatively higher social benefit.

$$Ecost_{i,j} = Ecost_{2020,j} \times \sqrt[\beta]{\frac{PGDP_{i,j}}{PGDP_{2020,j}}} \times \frac{Density_{i,j}}{Density_{2020,j}} \qquad (8)$$

$$EH_{benefit,i,j} = E_{2020,j} \times Ecost_{2020,j} - E_{i,j} \times Ecost_{i,j} \qquad (9)$$

where $Ecost_{i,j}$ and $Ecost_{2020,j}$ refer to the national monetized ecosystem damage cost in the years i and 2020, respectively, and β is the coefficient for ecosystem damage cost adjustment, which was obtained through analysing the relationship between past damage costs and PGDP and emission intensity.

The climate impact from NH_3 mitigation refers only to the alteration in the cooling effect that NH_3 emissions have on the Earth[51] resulting from the implementation of NH_3 mitigation strategies, as shown in equations (10) and (11). The GHG-related cobenefits or trade-offs resulting from NH_3 mitigation were not quantified in this assessment due to data and model limitations.

$$CI_{i,j} = CI_{2020,j} \times \sqrt[\gamma]{\frac{PGDP_{i,j}}{PGDP_{2020,j}}} \times \frac{Density_{i,j}}{Density_{2020,j}} \qquad (10)$$

$$CL_{benefit,i,j} = E_{2020,j} \times CI_{2020,j} - E_{i,j} \times CI_{i,j} \qquad (11)$$

where $CI_{i,j}$ and $CI_{2020,j}$ refer to the regional monetized climate impact in the years i and 2020, respectively, and γ is the coefficient for climate impact adjustment, which was obtained through analysing the relationship between historical damage costs and PGDP and emission intensity.

Future scenario setting
To explore how global NH_3 emissions may change under differing socioeconomic and policy conditions, this study conducted scenario analyses for the period 2020–2050 using the SSPs and RCPs, a framework widely applied in integrated assessment models and global environmental assessments such as the IPCC Sixth Assessment Report (AR6)[11,52]. In this study, we superimposed NH_3 mitigation ambitions, ranging from weak to strong policy efforts, onto four combined SSP–RCP scenarios (SSP1–1.9, SSP2–4.5, SSP3–7.0 and SSP5–8.5) to assess potential emissions trajectories, sectoral mitigation contributions

and associated societal costs and benefits. The four scenarios used in this study align with the standard CMIP6 pathways used in IPCC AR6 in terms of demographic, economic and energy trajectories. However, additional NH_3-specific mitigation assumptions (Extended Data Table 1 and Supplementary Tables 6 and 7) were overlaid to reflect plausible variations in policy ambition and abatement adoption within each scenario. These extensions allow sector-specific analysis of NH_3 mitigation potential and cost under internally consistent SSP–RCP frameworks[53]. This methodological approach builds on earlier nitrogen-focused SSP analyses[10] by incorporating NH_3-specific policies and linking them to broader sustainability and climate goals. Datasets on the future NH_3 emission-related activity levels such as fertilizer use, livestock population, manure management, agricultural land use and waste management were derived from the IIASA SSP Scenario Database[54] and peer-reviewed literature[10,55,56]. Detailed descriptions of the four scenarios and their characteristics are provided in Supplementary Information Section 2. Based on the quantifiable characteristics of the SSP–RCP, we integrated various NH_3 emission-reduction measures and strategies into the CHANS model to assess potential emissions trajectories, sectoral mitigation contributions and associated societal costs and benefits. Through this analysis, we aimed to identify the extent to which ambitious climate and sustainability pathways could also deliver substantial NH_3 reductions and, conversely, how business-as-usual trajectories may exacerbate emissions and their associated impacts.

Uncertainty analysis
To evaluate the robustness and reliability of our results, we conducted a comprehensive uncertainty analysis using Monte Carlo simulations. We performed 1,000 Monte Carlo iterations to quantify uncertainties in NH_3 emission inventories, mitigation potential, abatement costs and associated benefits across different sectors and regions. Our simulation framework incorporated uncertainties from multiple sources and their potential interactions: activity data (for example, fertilizer application rates, livestock populations and industrial production levels), emission factors specific to different NH_3 sources, technical parameters of mitigation measures (including mitigation efficiencies and implementation rates) and economic parameters (labour costs, market price and discount rates). Key parameters varied in the simulation included baseline emission factors (±15–30%, with larger uncertainties for non-agricultural sectors), mitigation efficiencies (±10–30%, depending on technological maturity), implementation costs (±20–50%, with regional variations) and activity data (±5–15%, based on statistical reporting uncertainty). The uncertainty ranges were sector specific, reflecting varying levels of data quality and understanding of emission processes. For example, agricultural emission factors had narrower uncertainty ranges due to extensive field measurements, whereas industrial and waste sector parameters had wider ranges reflecting limited data availability. We also considered parameter correlations and cross-sector interactions in our Monte Carlo framework. Cost–benefit calculations incorporated uncertainties in both monetary valuations of environmental benefits (for example, health impacts and ecosystem services) and region-specific discount rates. Detailed documentation of the simulation methodology and comprehensive results is provided in Supplementary Information Section 4 and Supplementary Tables 9 and 10.

Reporting summary
Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability
Shared Socioeconomic Pathways (SSPs) projections used for scenario modelling are publicly available from the IIASA SSP Scenario Database (https://iiasa.ac.at/models-tools-data/ssp). Data supporting the findings of this study are available within the article and its Supplementary

Information. Specific model parametrization is available upon reasonable request from the corresponding author. Source data are provided with this paper.

Code availability

No custom code was developed for this work. Data processing and statistical analyses were performed using Microsoft Excel (365), Origin (v.2025), ArcGIS Pro (v.3.3) and GraphPad Prism (v.10.1). All procedures are described in Methods.

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Acknowledgements

Author contributions

B.G. and X.Z. designed the study. X.Z. prepared and analysed the data. X.Z. and B.G. interpreted the results and wrote the first draft of the paper. Y.S. assisted with the data collection. Y.G. provided support for spatial visualization. M.S., H.G., W.W., S.Z. and S.L. provided important comments on the draft paper and edited the paper. All authors contributed to the discussion and revision of the paper.

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41893-025-01723-5.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41893-025-01723-5.

Correspondence and requests for materials should be addressed to Baojing Gu.

Peer review information *Nature Sustainability* thanks Frank Dentener and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

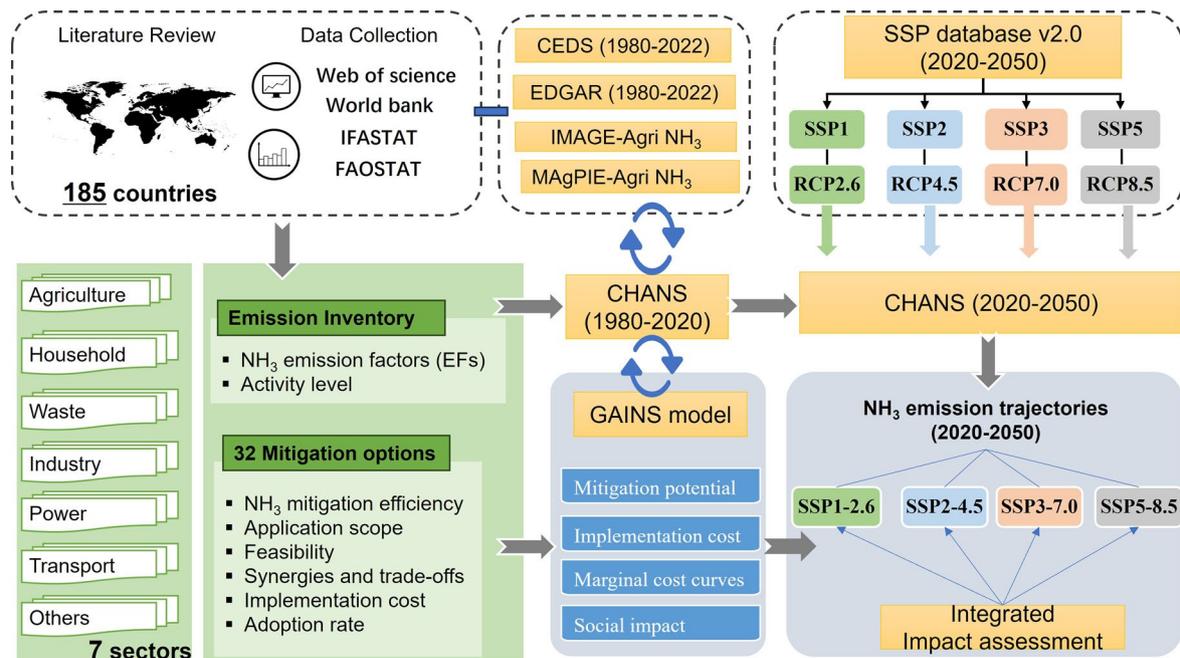**Reprints and permissions information** is available at www.nature.com/reprints.

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Extended Data Fig. 1 | Research Framework. This study adopts a comprehensive multi-model coupled assessment framework. Initially, a literature review and data collection were performed to get an overview of NH₃ emission inventory and mitigation options, followed by a comparative analysis of several model outputs or datasets to validate the current global and regional NH₃ emissions. Subsequently, the research evaluated mitigation measures across 7 sectors in 185 countries, utilizing the CHANS and GAINS models to assess their mitigation potential, implementation costs, and health, ecosystem, and climate impact.

Marginal abatement cost curves for NH₃ emissions across different regions/countries are generated to identify the cost-effective strategies for each. The final phase involved an examination of the varied future NH₃ emission trajectories, alongside their societal costs and benefits, under four Shared Socioeconomic Pathways–Representative Concentration Pathways (SSP-RCP) scenarios, spanning from 2020 to 2050. Credit: World map, flat curve graph and computer icons from SVG SiLH (svgsilh.com) under a Creative Commons license CC0 1.0.
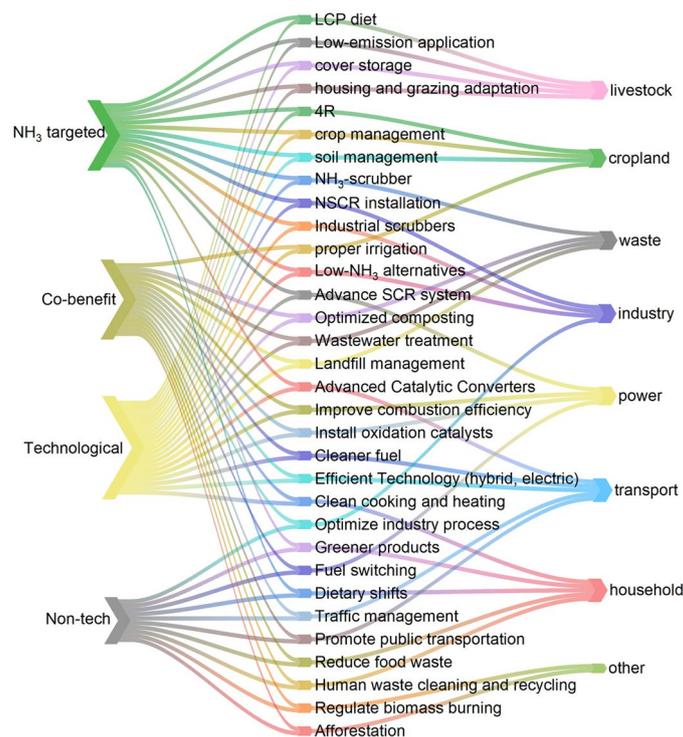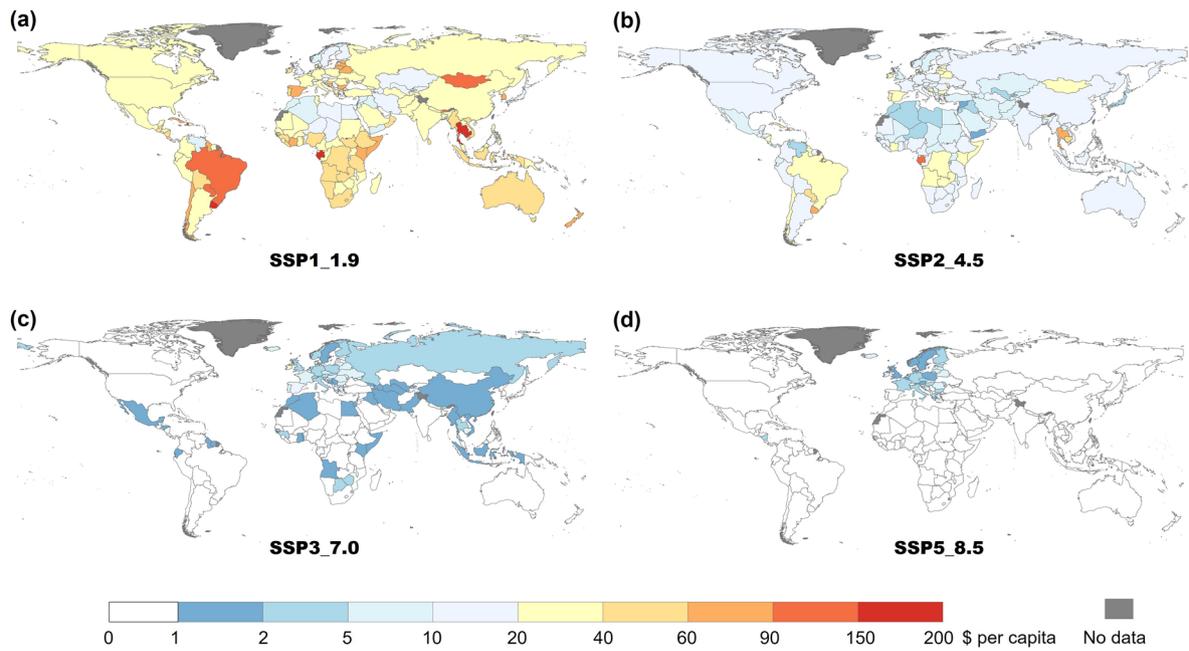
Extended Data Fig. 2 | Classification of NH₃ mitigation options. NH₃-targeted options are designed to reduce NH₃ emissions as their primary goal, co-benefit options are primarily targeted other objectives (for example, climate mitigation, water quality, health) but also reduce NH₃ as a co-benefit. Technological options directly rely on the use of physical technologies, infrastructure, or engineered systems to reduce NH₃ emissions. Non-tech options depend on changes in human behavior, management practices, policy frameworks, or institutional support, without necessarily requiring new physical technologies. Detailed descriptions of mitigation options could be found in supplementary Table 3-5.
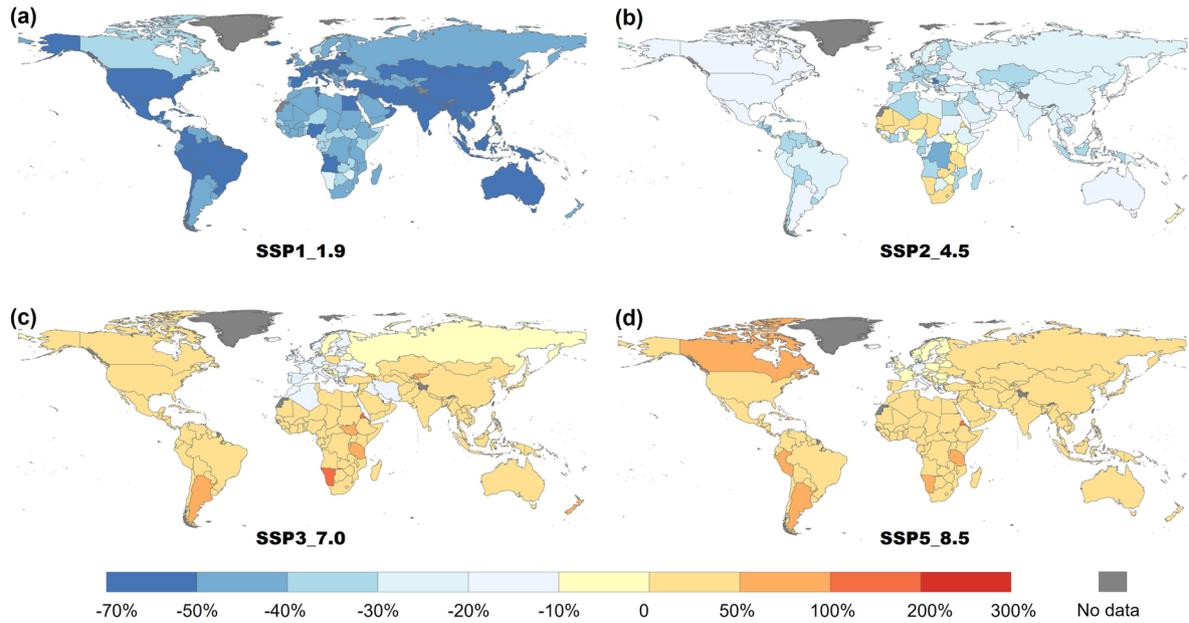
Extended Data Fig. 3 | NH$_3$ emission change (%) in 2050 compared to 2020 level under different SSP/RCP scenarios. a, **b**, **c**, **d** represents the relative changes (%) of NH$_3$ emissions from 2020 to 2050 under SSP1_1.9, SSP2_4.5, SSP3_7.0, and SSP5_8.5, respectively. Basemaps are sourced from GADM (https://gadm.org/).

Extended Data Fig. 4 | Spatial distributions of NH$_3$ mitigation cost ($ per capita) in 2050 under SSP/RCP scenarios. a, **b**, **c**, **d** represent the distribution of implementation cost for NH3 mitigation under SSP1_1.9, SSP2_4.5, SSP3_7.0, and SSP5_8.5, respectively. Basemaps are sourced from GADM (https://gadm.org/).
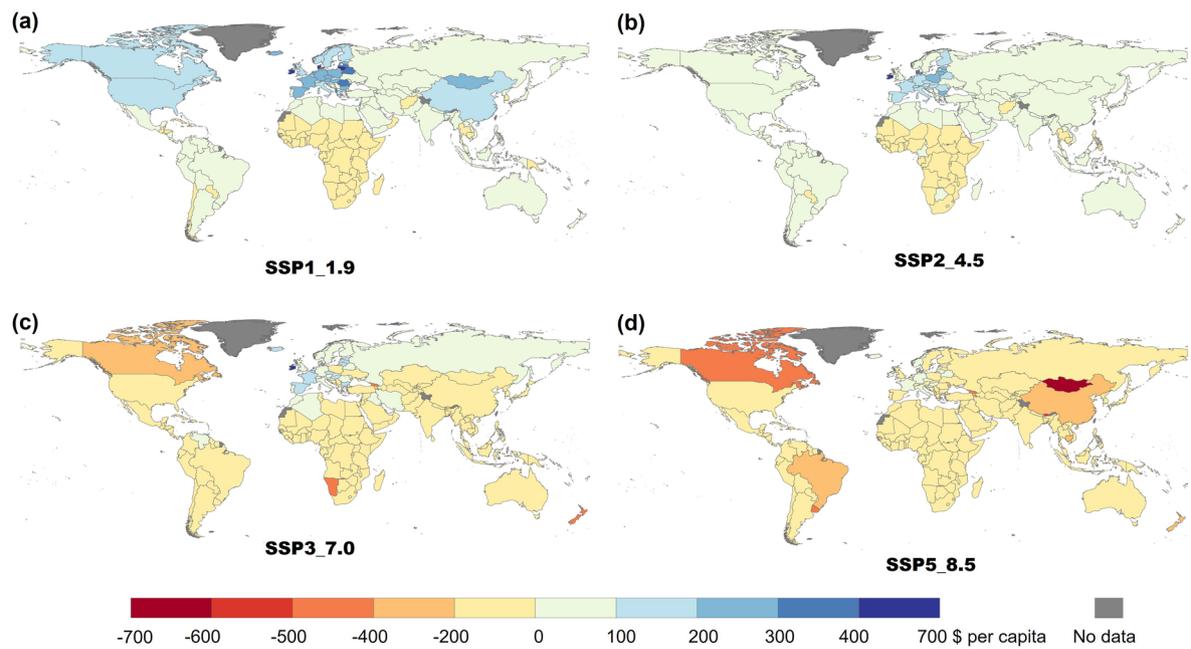
Extended Data Fig. 5 | Monetized impact of NH$_3$ emissions ($ per capita) in 2050 under SSP/RCP scenarios. a, **b**, **c**, **d** represent the distribution of the net monetized impact of NH3 emissions under SSP1_1.9, SSP2_4.5, SSP3_7.0, and SSP5_8.5, respectively. Basemaps are sourced from GADM (https://gadm.org/).
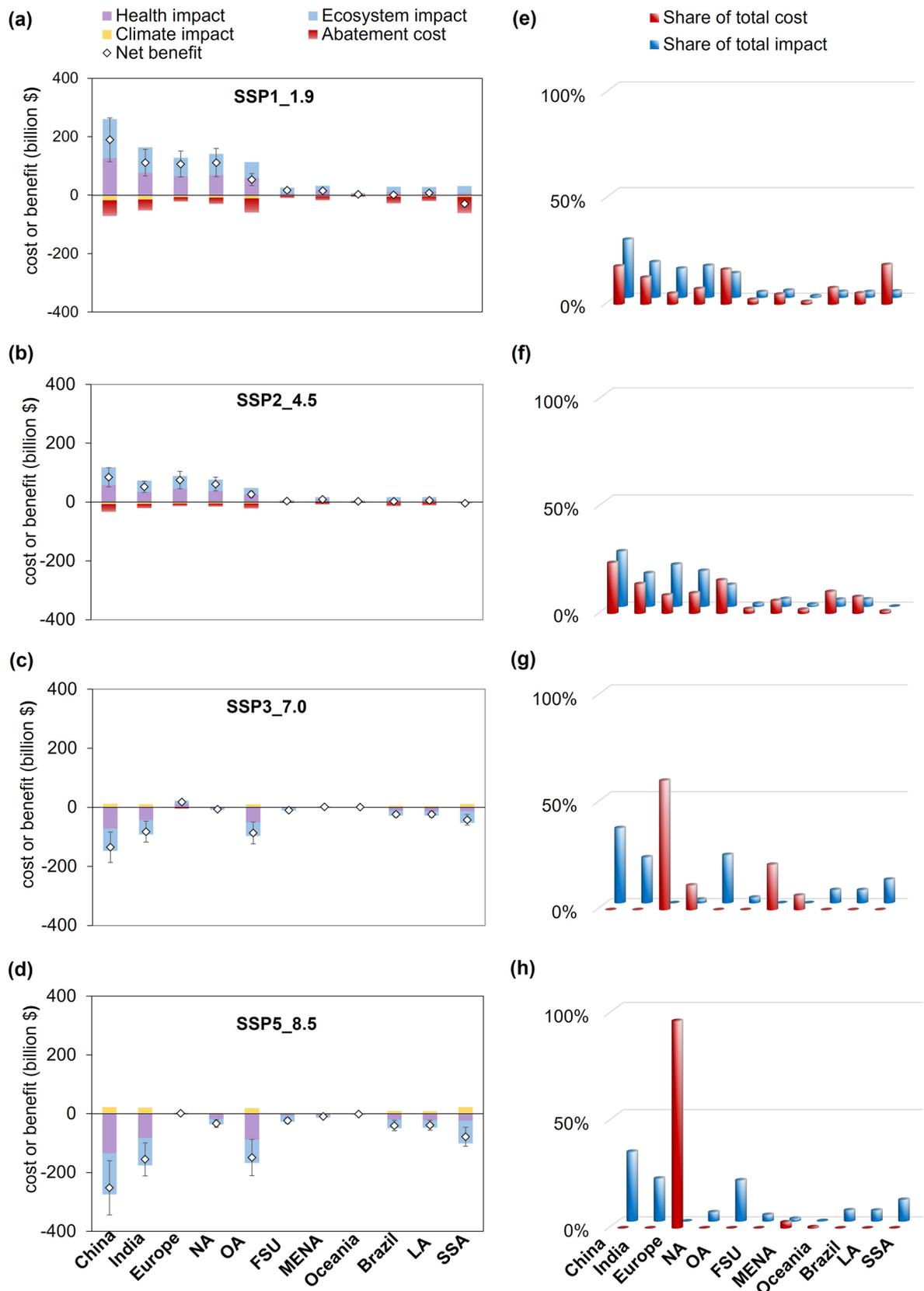
Extended Data Fig. 6 | Regional costs and benefits of NH₃ mitigation in 2050 under SSP/RCP scenarios. a, **b**, **c**, and **d** represent the regional impact assessment under SSP1_1.9, SSP2_4.5, SSP3_7.0 and SSP5_8.5, respectively; **e**, **f**, **g**, and **h** represent the regional shares of implementation cost and monetized impact under SSP1_1.9, SSP2_4.5, SSP3_7.0, and SSP5_8.5, respectively. Net benefits are presented as white diamonds (means) ± 95% confidence intervals, based on 1000 monte carlo simulations; negative value of impact denotes the damage cost.
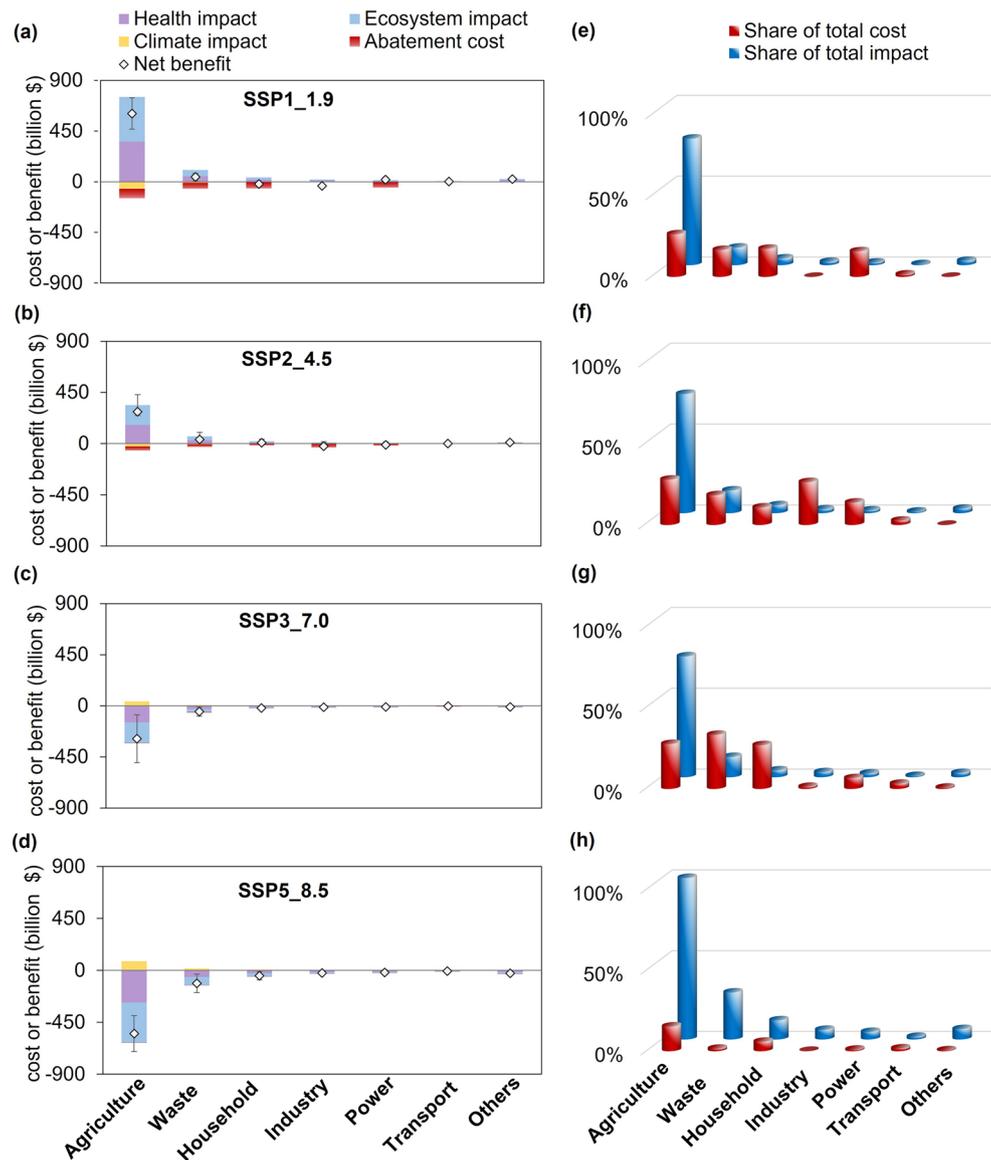
Extended Data Fig. 7 | Sectoral costs and benefits of NH₃ mitigation in 2050 under SSP/RCP scenarios. a, **b**, **c**, and d represent the sectoral cost and impact assessment under SSP1_1.9, SSP2_4.5, SSP3_7.0 and SSP5_8.5, respectively; **e**, **f**, **g**, and **h** represent the sectoral shares of implementation cost and monetized impact under SSP1_1.9, SSP2_4.5, SSP3_7.0, and SSP5_8.5, respectively. Net benefits are presented as white diamonds (means) ± 95% confidence intervals, based on 1000 monte carlo simulations; negative value of impact denotes the damage cost.

Extended Data Table 1 | Description of NH$_3$ mitigation ambition under different SSP–RCP pathways

	SSP1_1.9	SSP2_4.5	SSP3_7.0	SSP5_8.5
Road	Sustainability	Middle of the road	regional rivalry	fossil-fueled development
Public awareness of NH$_3$ mitigation	+++	++	+	*
Climate ambition	High	Medium	Low	Low
GHG emission	---	--	++	+++
Food demand	++	+++	++	+++
Animal products Consumption	++	+++	++	+++
Agricultural land area	--	-	+	++
Recycling of crop residues, animal manure, Food waste, and sewage	+++	++	-	-
Productivity in agriculture	+++	++	+	+
Adoption of mitigation techniques	+++	++	+	*
End-of-pipe technologies	+++	++	+	-
Clean alternative technologies	+++	++	+	-
NH$_3$ monitoring capabilities	+++	+	*	-
International cooperation	+++	++	-	*

Note: '+++', strong increase compared to the base year 2020, '++', moderate increase, '+', slight increase, '---', strong decrease, '–', moderate decrease, '-', slight decrease, * no changes. The scenario assumptions are qualitatively aligned with each SSP storyline. Detailed scenario descriptions can be found in Supplementary Text S2, quantitative assumptions on adoption rates and sectoral measures used for scenario modeling are provided in Supplementary Table S6-7.

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Corresponding author(s): Baojing Gu

Last updated by author(s): Oct 31, 2025

Reporting Summary

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Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed
☐	☒ The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement
☒	☐ A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☒	☐ The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☒	☐ A description of all covariates tested
☐	☒ A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☐	☒ A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☒	☐ For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
☒	☐ For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐ For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐ Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	All data were extracted from online database, text or tables directly, or figures using WebplotDigitizer 4.2.
Data analysis	Data analysis in this study were conducted at Microsoft Excel 365, 0rigin 2025, ArcGIS Pro 3.3, CHANS-Globe model, and GAINS 4.0 model. Simplfed CHANS calculator could be founded at https://person.zju.edu.cn/en/bjgu, and GAINS model framework can be found at https://gains.iiasa.ac.at/models/index.html.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:
- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

Shared Socioeconomic Pathways (SSPs) projections used for scenario modeling are publicly available from the IIASA SSP Scenario Database (https://iiasa.ac.at/

models-tools-data/ssp). Data supporting the findings of this study are available within the article and its supplementary information files. Specific model parameterization is available upon reasonable request from the corresponding author.

Research involving human participants, their data, or biological material

Policy information about studies with human participants or human data. See also policy information about sex, gender (identity/presentation), and sexual orientation and race, ethnicity and racism.

Reporting on sex and gender	not applicable
Reporting on race, ethnicity, or other socially relevant groupings	not applicable
Population characteristics	not applicable
Recruitment	not applicable
Ethics oversight	not applicable

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	This study conducted a literature review and data collection to compile an updated NH3 emission inventory (1980-2020) in 185 countries and selected 32 feasible mitigation options across seven sectors globally. Mitigation potential, implementation costs and social benefits were then evaluated based on a set of SSP-RCP scenarios to inform future mitigation strategy and pathways.
Research sample	This study incorporated regional NH3 emission data of 185 counties across 7 sectors (Agriculture, household, waste, energy, industry, and transport, others) globally during 1980-2020, and selected a group of 32 mitigation options for the integrated assessment of global and regional mitigation potential and cost-benefit analysis.
Sampling strategy	we adopted a comprehensive inclusion strategy, integrating all relevant mitigation options identified from peer-reviewed literature, technical reports, and international emission databases. Countries and regions were consistently included according to global classification systems (FAO, World Bank, SSP/CMIP6 regions). This approach ensured that the analysis captures the complete diversity of emission sources, technologies, and socioeconomic contexts without bias toward particular regions or sectors.
Data collection	Data used in this study were collected from global/regional statistics, surveys, reports, published papers with field experiment results, and emission databases (EDGAR, CEDS, SSP database and the CHANS model).
Timing and spatial scale	This study complied the global NH3 emission inventories, covering 185 counties' local information in the past four decades (1980-2020) across 7 sectors. The high-resolution emission patterns were mapped on the national scale in 2020. Four SSP-RCP scenarios from 2020 to 2050 were simulated to identify global and regional cost-effective NH3 management pathway.
Data exclusions	No data were excluded from the analysis.
Reproducibility	All attempts to repeat the results of this study were successful.
Randomization	Randomization was not applicable. This study is based on modeling and synthesis of global data, not on experiments or surveys involving human or animal subjects. All countries, regions, and mitigation options were systematically included according to defined criteria rather than selected at random.
Blinding	Blinding was not necessary as none of the data used in this study was subjective nor could be influenced by researcher biases.

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern
☒	☐ Plants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging