

Accelerated attainment of global air quality standards with disproportional health co-benefits under the 1.5 °C target

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Meeting the Paris Agreement targets and the World Health Organization 2021 Air Quality Guidelines is crucial for avoiding air pollution-related health damage. Failing these targets worsens climate change, intensifying environmental threats to public health. Here, we adopt an integrated assessment modeling framework to evaluate timelines for the AQGs attainment under different mitigation scenarios worldwide. We find that achieving 1.5 °C goal could expedite guidelines by decades, dropping PM_{2.5} to 5 µg m⁻³ and ozone to 30 parts per billion by volume by 2050, averting over a million mortalities and delivering major benefits in India, China, American, Europe, and Southeast Asia. Monetized health co-benefits would exceed mitigation costs, rising from 11 trillion to 22 trillion US dollars between 2050 and 2100. We show heightened climate ambition is both feasible and economical, offsetting global mitigation expenses via health benefits. Insufficient actions would exacerbate climate risks such as extreme weather, sea-level rise and economic loss.

Global greenhouse gas (GHG) emissions continued to increase to 59 (± 6.6) Gigatons (Gt) in 2019, with the cumulative emissions reaching four-fifths of the total GHG budget for the 1.5 °C target¹. It is projected that even if the submitted Nationally Determined Contributions (NDCs) are fully implemented, the global average temperature would probably rise by 3 °C², implying that achieving well below 2 °C climate target requires more decisive and immediate climate actions toward carbon neutrality by the mid-century³. In the meantime, the World Health Organization (WHO) Air Quality Guidelines (AQGs) in 2021, which set the annual concentration standards for PM_{2.5} at 5 µg m⁻³ and peak-season ozone at 60 µg m⁻³, requires upstream energy and industrial structural change in addition to the adoption of end-of-pipe control measures⁴.

Previous studies have shown that climate change mitigation could significantly improve future air quality and human health^{5–11}.

The avoided welfare losses (or welfare benefits) can partially or entirely offset the costs of mitigation policies^{12–16}, especially in the countries that have actively announced ambitious climate commitments and could obtain the bulk of health co-benefits by the mid-century^{17,18}. Moreover, achieving well below 2 °C target, however, requires global decisive action, especially after 2050, and further efforts from Africa, Latin America, and Southeast Asia, whose populations and economies are rapidly expanding. Despite this, many studies focus mostly on avoided mortality in developed countries, while ignoring additional health expenditure savings and underrepresenting other fast-growing emitters. Furthermore, most research addresses only moderate climate or air quality targets in country- and region-level, leaving significant gaps. Uncertainty remains about how a more ambitious 1.5 °C goal might affect attainment of the AQGs, and how much health co-benefits could

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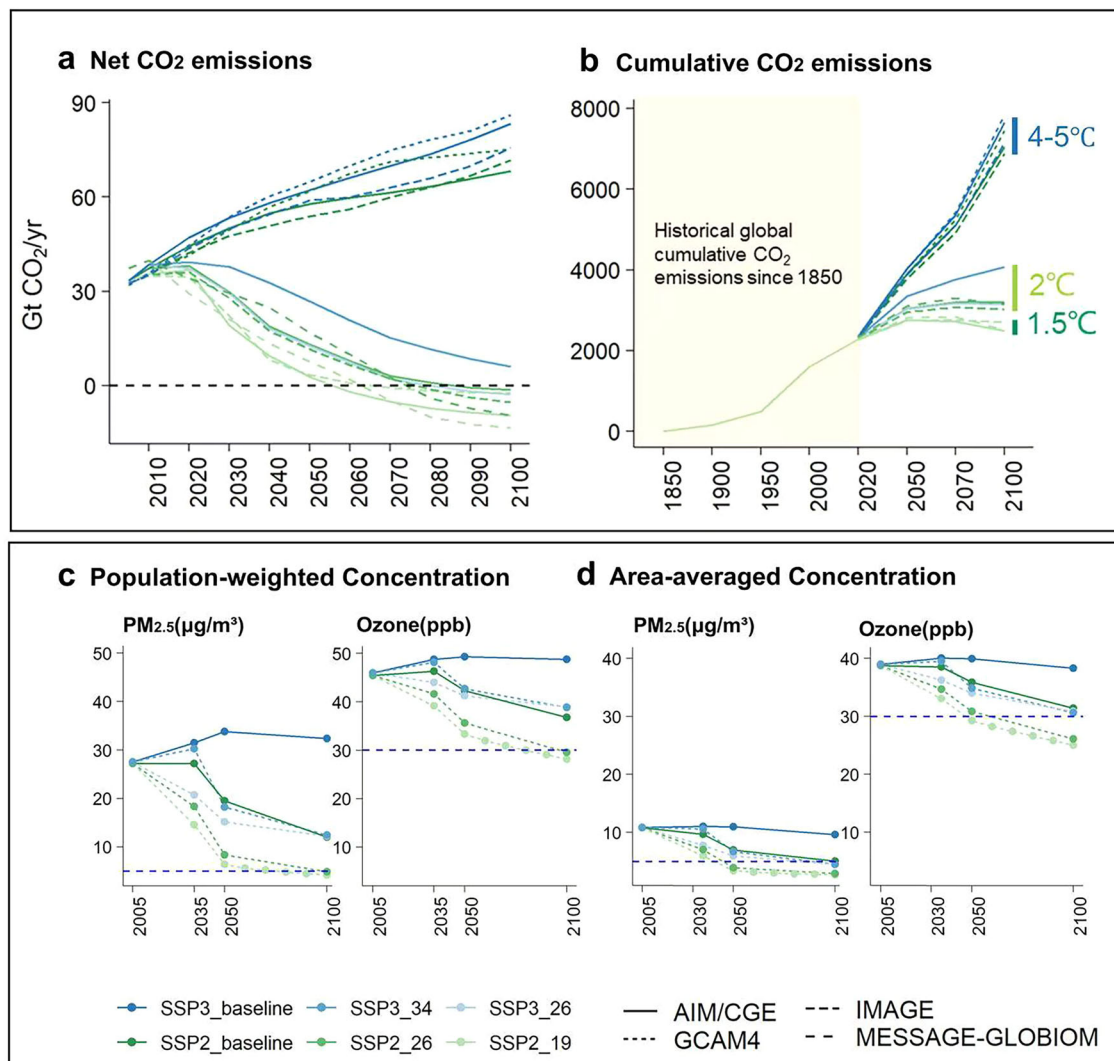


Fig. 1 | Global CO₂ emissions and pollutant concentrations in different scenarios evaluated by four prevailing Integrated Assessment Models (IAMs). **a** Global net CO₂ emissions from 2010 to 2100; **b** Global cumulative CO₂ emissions from 1850 to 2100; **c** Population-weighted concentrations of PM_{2.5} and ozone; **d** Area-averaged concentration of PM_{2.5} and ozone. AIM/CGE: Asia-Pacific

Integrated Model / Computable General Equilibrium model; IMAGE: Integrated Model to Assess the Global Environment; GCAM4: Global Change Assessment Model, version 4; MESSAGE-GLOBIOM: Model for Energy Supply Strategy Alternatives and their General Environmental Impact-Global Biosphere Management Model.

offset mitigation costs worldwide amid evolving socio-economic conditions beyond 2050^{19,20}. To bridge these gaps, it is necessary to investigate how different global regions could gain air-quality-related co-benefits from deep decarbonization, which is vital to simultaneously promote global collective efforts to pursue ambitious climate and air quality targets.

In this work, we adopt an integrated assessment modeling approach to investigate the implications of the ambitious 1.5 °C–2 °C climate targets on accelerated timelines of attaining the AQGs worldwide in an extended period by 2100, especially in Africa, Latin America, and Southeast Asia. We combine the AIM/CGE (Asia-Pacific Integrated Model/Computable General Equilibrium) model, CAM-chem (Community Atmosphere Model with Chemistry) model and IMED | HEL (Integrated Model of Energy, Environment and Economy for Sustainable Development | Health module) model. IMED | HEL model also uncovers the additional disproportional health co-benefits and health expenditure savings of enhanced climate ambition from 2 °C to 1.5 °C in different countries and regions. Accordingly, this study contrasts the temporally and regionally varied health co-benefits versus climate mitigation costs.

Results

Gaps between national pledges and global climate AQG targets

In the baseline scenarios of Shared Socioeconomic Pathways2 (SSP2) and SSP3, the annual global CO₂ emissions will continue to grow by the end of this century, ranging from 55 to 86 Gt (Fig. 1a) in 2100, as projected by four prevailing integrated assessment models (IAMs) adopted by the Intergovernmental Panel on Climate Change (IPCC) assessment reports. As a result, the cumulative CO₂ emissions from 2020 to 2100 amount to over 5000 Gt, even far above the tight remaining emissions space of 550–850 Gt CO₂ equivalent for all GHG considering their global warming potential (GWP) in line with the 1.5 °C–2 °C targets (Fig. 1b). Moreover, achieving the Paris Agreement target requires reaching global net-zero CO₂ emissions by around 2055 before entering the negative emissions era to save emission spaces for residual non-CO₂ GHGs such as CH₄ and N₂O (Supplementary Fig. 1). The relationships between CO₂ emission reduction and non-CO₂ GHGs emission reductions are shown in Supplementary Fig. 2 (2050) and Supplementary Fig. 3 (2100).

Unlike GHGs, due to currently stated legislations on air pollution control implicitly reflected in the baseline scenarios, most countries

and regions are on the track of decoupling their socio-economic development from air pollutant emissions, which will remain constant or decline in the coming decades. Remarkably, in the SSP2_baseline scenario, China's shares of most conventional air pollutants emissions, e.g., NO_x and SO_2 , to the world would peak at 24–26% by 2030 and then drop to 8–12% by 2100. By contrast, the shares of emissions in Sub-Saharan Africa, India and Latin America would increase from 4 to 12%, 8–11% and 7–10% in 2020 to 11–18%, 13–14% and 10–13% in 2100, respectively, as a result of the socio-economic development and relatively weak environmental policies, reflected in the large implementation gap between stated targets and on-the-ground measures^{1,21,22}. Nevertheless, achieving the AQGs is difficult, if not impossible (Fig. 1c). By 2100, the global population-weighted annual $\text{PM}_{2.5}$ and ozone would be $13 \mu\text{g m}^{-3}$ and 37 parts per billion by volume (ppbv) under the SSP2_baseline scenario, which lie significantly higher than the AQGs.

Keeping 1.5°C within reach accelerates AQGs worldwide by decades

With the current legislation in force, as implicitly represented in the SSP2_baseline scenario, global air quality improvement is highly heterogeneous worldwide. For population-weighted $\text{PM}_{2.5}$, Latin America, Africa, the United States and Canada will approach the WHO recommendation standard of $5 \mu\text{g m}^{-3}$ before 2050. However, for these countries and regions like Europe, Japan, China, India, Southeast Asia and the rest of Asia, $\text{PM}_{2.5}$ concentration will persistently exceed $5 \mu\text{g m}^{-3}$ throughout this century. As for ozone, almost none of the 17 regions could attain the AQGs except for Latin America and Oceania, whose background concentrations are already low.

Encouragingly, achieving the 1.5°C target under the SSP2_19 scenario will bring substantial co-benefits in air pollutant emissions reduction, especially for SO_2 and NO_x in Asia, the Middle East, and Africa after 2050 (Supplementary Fig. 4-11), which brings opportunities for further improvement in global air quality. For instance, the global population-weighted $\text{PM}_{2.5}$ concentration would be close to $5 \mu\text{g m}^{-3}$ by around 2050, while ozone would be around 30 ppbv in 2060 (Fig. 1c-d). Meanwhile, most regions except for economies in transition and India could attain the AQGs by the end of this century. Moreover, enhanced climate ambitions could significantly advance air quality improvement. For instance, the SSP2_26 scenario will hold the global population-weighted $\text{PM}_{2.5}$ and ozone concentrations compatible with AQGs as late as 2100, whereas the SSP2_19 scenario could accelerate the attainment to around 2060 for $\text{PM}_{2.5}$ and 2080 for ozone (Fig. 1c, d). Regionally, the United States will achieve the air quality target in 2035 in the SSP2_19 scenario instead of 2050 in the baseline scenario, whereas Europe, Japan, China and North Africa could attain it in 2050 instead of 2100. As for ozone, 13 out of 17 regions could attain the AQGs in the SSP2_19 scenario. Nonetheless, most regions meet the AQGs for ozone after 2070, significantly later than $\text{PM}_{2.5}$.

When comparing the timelines of net-zero carbon emissions and the AQGs (Supplementary Table 1), our results show that Africa and Latin America driven by agricultural activities rather than heavy industries will achieve the AQGs in around 2035, which is noticeably before the net-zero carbon emissions year between 2040 and 2060. By contrast, China and India will reach the air quality target (after 2060) later than the net-zero carbon emission year (around 2050). Meanwhile, many countries and regions can achieve the AQGs for $\text{PM}_{2.5}$ before net-zero carbon emissions, while ozone targets will fall far behind, such as Japan, the United States, and North Africa, which are either developed countries and regions or have relatively better air quality now.

In the SSP2_19 scenarios, an estimated 380 million $\text{PM}_{2.5}$ -related and ozone-related premature deaths could be avoided globally from

2020 to 2100, though regional disparities persist. India (109 million, 29% of the world total), China (97 million, 26%), and Southeast Asia (41 million, 11%) lead in combined avoided deaths. Of the two pollutants (Fig. 2a, b), $\text{PM}_{2.5}$ remains the dominant pollutant, with around 303 million avoided deaths—four times that of ozone (76 million). Under SSP2_19, India's $\text{PM}_{2.5}$ -related avoided mortality reaches 87 million (29%), compared to 71 million (29%) under SSP2_26. China's avoided $\text{PM}_{2.5}$ deaths increase from 61 million (25%) under a 2°C scenario to 82 million (27%) under SSP2_19, while Southeast Asia, the rest of Asia, economies in transition, and Western Europe each see 10–33 million avoided fatalities. A similar distribution applies to ozone-related deaths, though on a smaller scale, with China's share dropping to 19–21%. Noticeably, even by 2050, when many countries and regions approach carbon neutrality, approximately 1.6 billion and 6.9 billion people remain exposed to $\text{PM}_{2.5}$ and ozone above the AQGs (Supplementary Fig. 18–19).

Early action yields disproportional health co-benefits

In addition to an apparent temporal mismatch between the global maximum health co-benefits in 2050 and carbon reductions in 2100 (Fig. 3a), there are significant regional disproportionalities over time. For instance, the United States and China are the top contributors to global carbon reductions in 2050, while in 2100, regional contributions would be more equally distributed with more balanced reductions from India, economies in transition, Western Europe and the rest of Africa (Fig. 3c and Fig. 3d). Similarly, there will be a significant shift in regional health co-benefits from 2050 to 2100. Globally, the total health co-benefits of avoided premature death will decrease slightly from 1.08 million in 2050 to 0.96 million by the end of this century. On the other hand, the regional health co-benefits would persistently dominate in India, China, Southeast Asia and the United States, accounting for around 28%, 23%, 11% and 8% of the global total by 2050, respectively. Conversely, in 2100, the shares of India and Western Europe will expand to 30% and 9%, respectively, whereas that of China will diminish to 14%.

Furthermore, the co-benefit defined as avoided premature deaths and carbon reduction in different scenarios shows significant regional disproportionalities over time (Fig. 3b). From SSP2_baseline to the SSP2_26 scenario, carbon reduction will bring 0.814 million avoided mortality, while it will be 0.267 million from SSP2_26 to SSP2_19 scenario in 2050. China, the United States and economies in transition are the top three carbon reduction contributors, and India, China and Southeast Asia are the top three countries and regions with the highest health benefits (Fig. 3c). In 2100, the carbon reduction ratio will increase fast, and except India, China and Southeast Asia, Europe-25 will also have significant health co-benefits. In terms of health expenditure saving, work time loss, and carbon reduction will also bring significant benefits (Supplementary Figs. 22–23). Moreover, more ambitious climate actions under the SSP2_19 scenario will noticeably increase the benefit ratio for most countries and regions before 2050, indicating early actions in the coming two decades are critical to obtaining health co-benefits more effectively.

Health co-benefits outweigh mitigation costs, but with regional disparities

Although the regional mitigation costs under the SSP2_26 scenario are huge, they could be offset by the monetized co-benefits of avoided air pollution-related mortality alone in many regions (Fig. 4a). As most countries and regions successfully transit into low-carbon economies, the rest of Africa and India will face the highest mitigation costs due to relatively higher dependence on fossil fuels resulting from potential reluctance on early decarbonization. On the other hand, in terms of monetized health co-benefits, China, India, the United States and Western Europe will take the lead before 2050, whereas Western

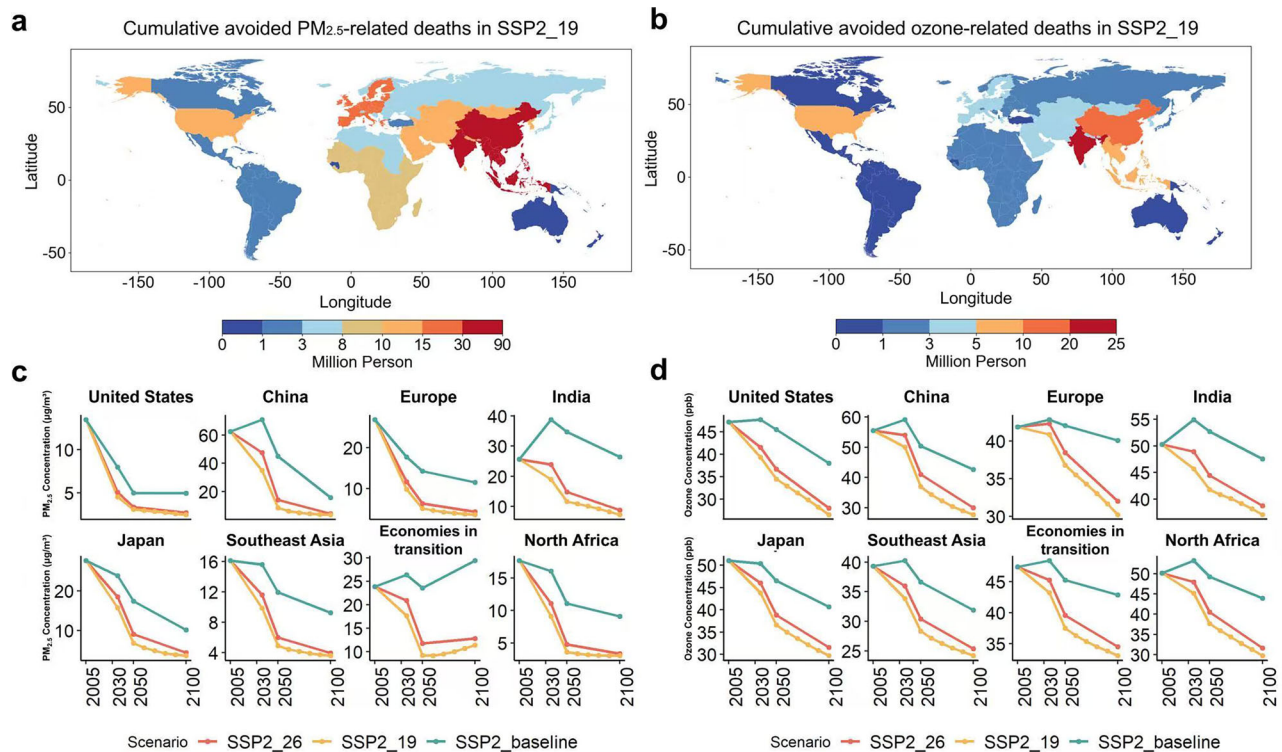


Fig. 2 | Cumulative avoided pollutant-related mortality and pollutant concentrations. **a** Cumulative avoided $\text{PM}_{2.5}$ -related mortality in the SSP2_19 scenario compared to the SSP2_baseline scenario during 2005–2100; **b** Cumulative avoided

ozone-related mortality in the SSP2_19 scenario compared to the SSP2_baseline scenario during 2005–2100; **c** Population-weighted $\text{PM}_{2.5}$ concentration in different scenarios; **d** Population-weighted ozone concentration in different scenarios).

Europe, India and Southeast Asia will be the top three countries and regions in 2100. As a result, the global net benefits of achieving 1.5°C target will increase over time from about 11 trillion US dollars in 2050 to 22 trillion US dollars in 2100 in the SSP_19 scenario. Nevertheless, when shedding light on the regional distribution, it turns out that the net benefits exhibit distinguished regional heterogeneity. Due to limited co-benefits in air quality improvement, some countries and regions, including Canada, Brazil, Oceania, Latin America, and Africa, will witness near zero or even negative net benefits. By contrast, tremendous net benefits could be gained in the United States, China, India, Europe, and Southeast Asia due to remarkable air quality improvement, moderately high per capita income and high population density. These top five countries and regions account for over 80% of the total global net benefits in all scenarios.

Another key indicator is the additional net benefits associated with the enhanced 1.5°C target compared to the 2°C target. Our estimates indicate that the global additional net benefits are projected to increase from 9.74 to 11.04 trillion US dollars by 2050 but decrease slightly from 22.85 to 21.91 trillion US dollars by 2100 (Fig. 4b). These results suggest that while enhancing climate ambition demonstrates economic viability in the short term, its long-term net benefits may plateau or decline, warranting further investigation into its sustainability and broader impacts (Fig. 4b). However, the regional landscape will present a mixed trend. For example, the top four countries and regions are China, India, the United States, and Southeast Asia, and this trend will persist until 2050 except for India, the Middle East and the rest of Africa. In 2100, although the additional benefits are still positive in China, Western Europe, economies in transition and the rest of Europe, they will decline significantly compared with 2050, even to negative in India, the Middle East, the rest of Africa and the United States.

Compared with the data from World Economic Forum²³, the avoided health-related economic losses associated with air pollution

alleviation under SSP2_19 and SSP2_26 by 2050 compared to SSP2_baseline scenario will be 16.5 and 14.5 times higher than the economic losses due to climate change under SSP2_2.6, respectively (Fig. 5). Asia experiences both the highest avoided health-related economic losses from air pollution alleviation and the most considerable economic losses resulting from climate change. South America experiences the highest economic losses attributable to air pollution, while the economic losses resulting from climate change rank third. The Southwest Pacific region will suffer economic losses from air pollution in both scenarios, while the economic losses from climate change would be the least of all regions. The European region ranks second among all regions in terms of avoided economic losses from air pollution alleviation under both scenarios, and it ranks second in terms of economic losses from climate change.

Discussion

Using multiple well-established integrated assessment approaches and databases, this study highlights that achieving the 1.5°C climate targets could accelerate the attainment of the the AQGs globally, leading to substantial health co-benefits that exceed climate mitigation costs in most major economies. We also find that the current legislation on air pollution control is insufficient for most countries and regions to achieve the AQGs for $\text{PM}_{2.5}$ and ozone within this century, especially in the Asian countries, whose economies are still heavily dependent on fossil fuels. By contrast, with the transformative energy and industrial structure change triggered by the enhanced 1.5°C climate target, the AQGs for $\text{PM}_{2.5}$ could be attained before 2050 and accelerated by decades in industrialized countries. Even in China and India, the AQGs for $\text{PM}_{2.5}$ could be achieved by around 2080. Moreover, the AQGs for ozone are also achievable, although much more challenging and later than $\text{PM}_{2.5}$. For instance, in some countries such as Turkey, China and the United States, the AQGs for ozone could only be achieved by around 2070, while European countries and Japan could not achieve it

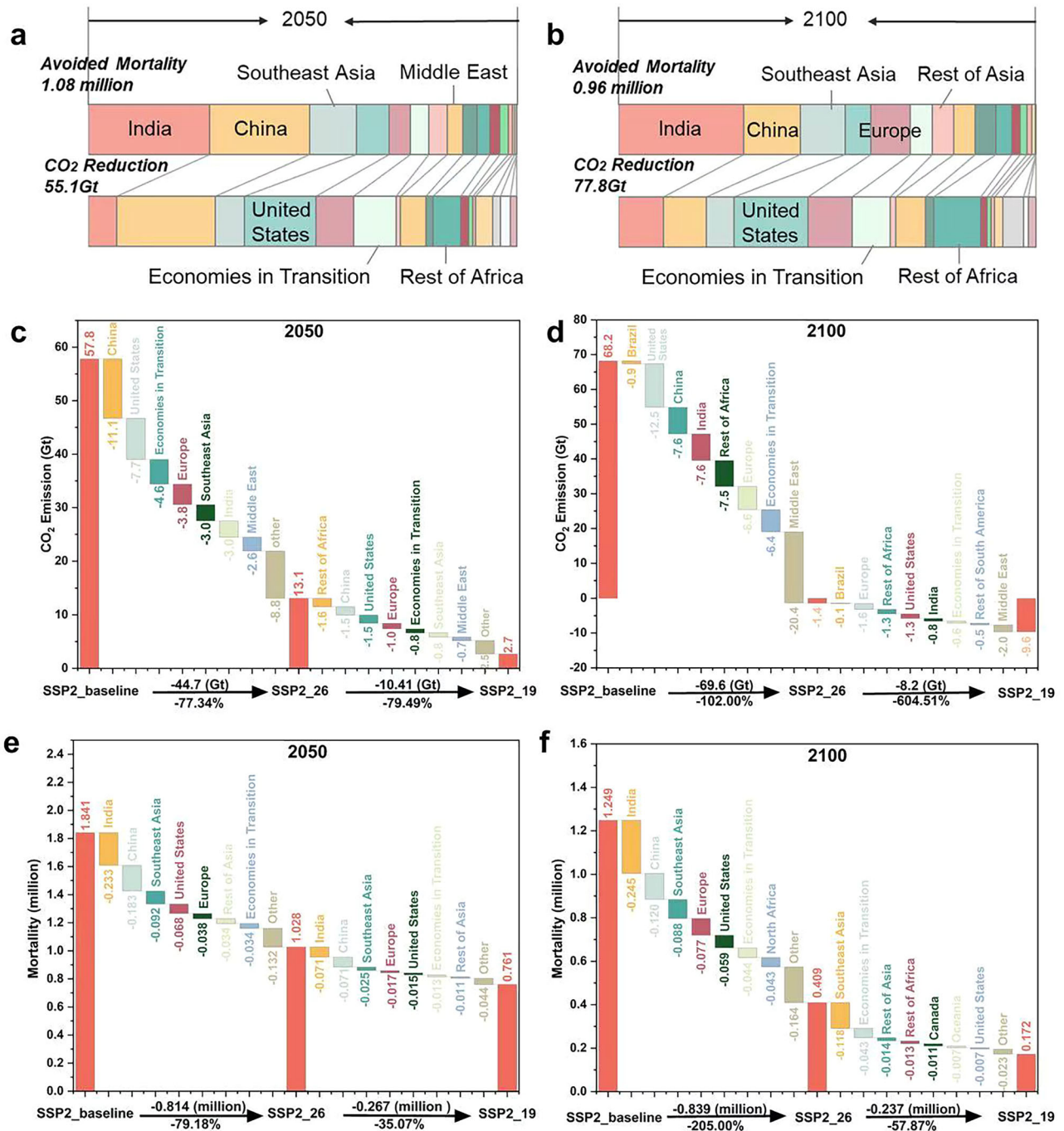


Fig. 3 | Mortality and CO₂ emissions among 17 regions in 2050 and 2100. Comparisons between the shares of avoided mortality and CO₂ reductions in the SSP2_19 scenario compared with SSP2_baseline **a** in 2050 and **b** in 2100; Changes in

CO₂ emissions from SSP2_baseline to SSP2_26 and SSP2_19 **c** in 2050 and **d** in 2100; Changes in avoided mortality from SSP2_baseline to SSP2_26 and SSP2_19 **e** in 2050 and **f** in 2100.

until 2100. Moreover, the AQGs for ozone are also achievable, although much more challenging than PM_{2.5}, due to its nonlinear response to its precursors, including NO_x and VOCs, and also the influences from climate change.

We also highlight that ambitious early climate actions prove viable, both in terms of co-benefit effectiveness and additional net health co-benefits. The physical health co-benefits of avoided premature deaths from more ambitious climate mitigation could be felt immediately in the nearer term before 2050. By comparing the mitigation costs with monetized health co-benefits, it is found that the global net benefits would persist throughout the whole century, most of which are obtained in Asian countries²⁴, home to half of the

global population. Regionally, in addition to China and India, which will enjoy about half of the global health co-benefits, the United States and Western Europe will also benefit substantially. Coincidentally, these four countries and regions are most active in developing and deploying low-carbon solutions such as renewable energy, electric vehicles, energy storage, and carbon capture storage technologies. Such technologies are key to reducing carbon costs, fostering new economic growth engines, and gaining an edge in economic competitiveness in the long term. Therefore, although deep decarbonization may trigger near-term economic pains for the traditional industries that comprise the backbone of their current economic structure, such short-term losses will hopefully be

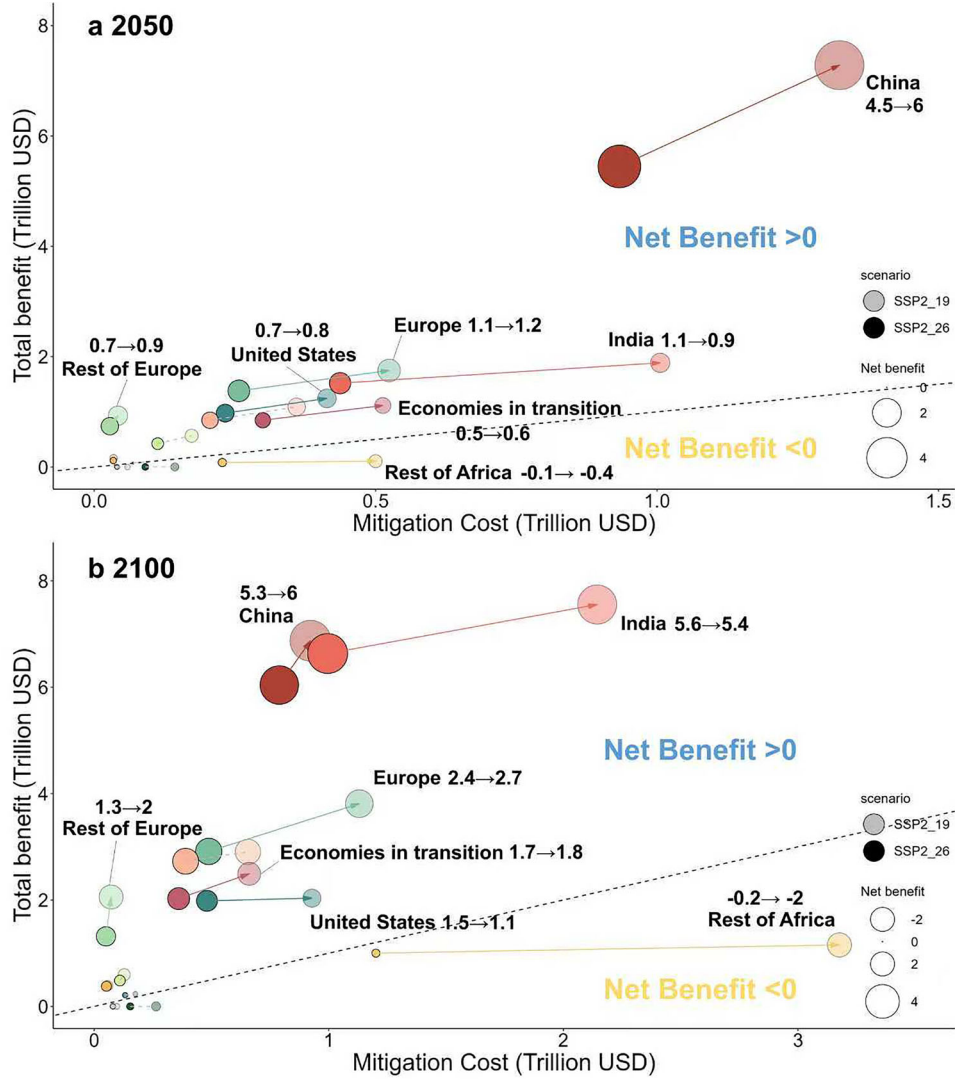


Fig. 4 | Cost-benefits analysis in the SSP2_19 and SSP2_26 scenarios among 17 regions. a Mitigation costs and total benefits among 17 regions in 2050; **b** Mitigation costs and total benefits among 17 regions in 2100; The US dollars is the constant price in 2010. (the labeled numbers represent net benefits changed from SSP2_26 to SSP2_19).

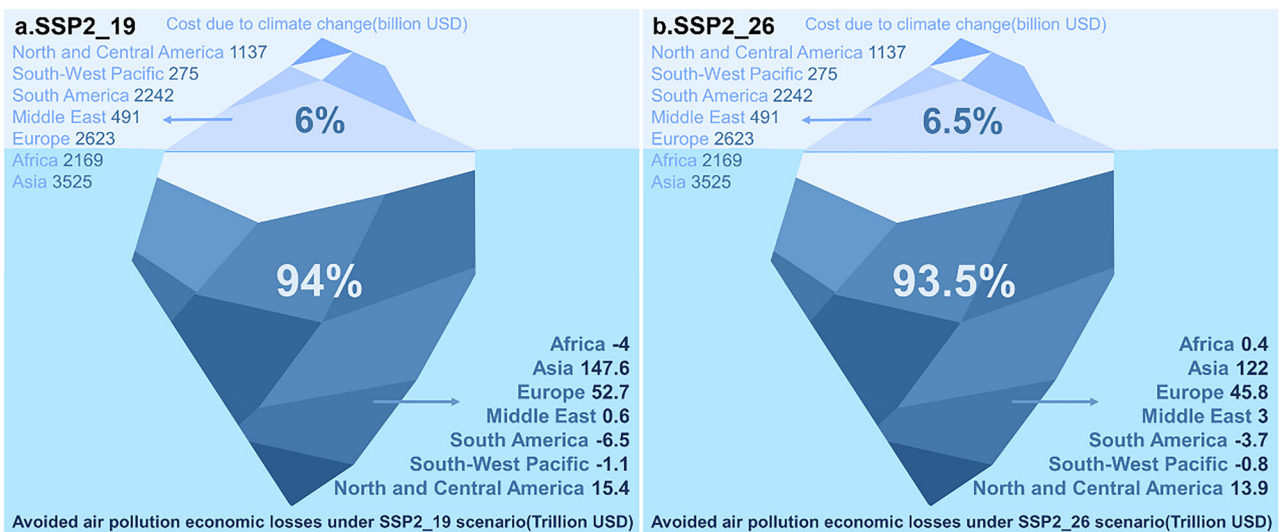


Fig. 5 | Global economic losses associated with climate change impacts and air-pollution-related damages up to 2050. a Comparison of avoidable economic losses from air pollution under the SSP2_19 scenario up to 2050 with the economic losses from climate change under the SSP2-RCP6 scenario. **b** Comparison of avoidable economic losses from air pollution under the SSP2_26 scenario up to 2050 with the economic losses from climate change under the SSP2-RCP6 scenario.

compensated by long-term economic gains, even though they may take decades to realize.

Countries face varied climate challenges and opportunities depending on their development patterns and conditions. For instance, in the countries still undergoing fast industrialization and urbanization, the next two decades are the critical periods determining whether carbon and air pollution will be locked in or decoupled from the newly sold durable goods and newly built long-life infrastructure. If these countries could pursue lower-carbon industrialization and urbanization processes enabled by zero-carbon technologies, a double dividend of near-term high health benefits and long-term competitive economic gains could be obtained²⁵. Conversely, even though considering air quality-related co-benefits alone cannot convince certain countries and regions to take bold climate actions, they deserve a second thought. For instance, if the Middle East overlook the tide of carbon neutrality and hesitate to take decisive actions to foster alternative industries to substitute their current fossil backbone industries gradually, they will likely miss the narrow window to take a transformative leapfrog, and ultimately fall behind economically as the world shifts away from fossil fuels in the longer term. Meanwhile, for the Latin America and Africa, deep decarbonization is also essential as they emit huge amounts of non-CO₂ from the agricultural, forest and land-use (AFOLU) sectors, which to some extent determines the success of achieving 1.5°C target. Therefore, they must be supported with international financial and technological aid to cut the hard-to-abate non-CO₂ gases.

The sensitivity analysis reveals that although alternative socio-economic conditions, exposure-response relationships and Value of Statistical Life will affect the numerical values of premature deaths and the monetized mortality, they will not alter the major findings and overall conclusions, suggesting the robustness of this study (Supplementary Note 5, Supplementary Fig. 24–26). More specifically, health co-benefits under the most sustainable socio-economic baseline scenario of SSP1 are the lowest since it is an ideal case assuming all regions will turn green proactively. By contrast, the SSP3 mitigation scenarios would generate the highest co-benefits compared with the high-carbon baselines. With the sensitivity analysis, our study captures the distribution space of the co-benefits under different socio-economic conditions and mitigation efforts, confirming the robustness of the cost-benefits for the policymakers to take bolder actions. We use the Kaya formula to quantify the influences of pollutant concentration and population change (Supplementary Note 6, Supplementary Fig. 27). We compared with GBD2019 dataset and satellite-derived concentration in 2005, our simulation concentration is slightly lower than both of them, especially in Africa and South Asia. PM_{2.5} health estimated in our study could be conservative since the coarse resolution model adopted in our study could potentially underestimate the PM_{2.5} exposure.

Last but not least, this study opens up various directions for future research. For instance, climate policies are implemented here as identical carbon prices applied globally, which could avoid debate over regional emission budget allocation but may entail equity and feasibility concerns as the Africa and Latin America would face disproportionately heavier burdens of carbon reduction costs. Meanwhile, costs and benefits are not fully reflected in the current modeling framework. For instance, technological learning effects may reduce climate mitigation costs in the longer term, while climate mitigation could also reduce health damage from extreme weather events such as heatwaves, bringing additional health and economic benefits. Under future climate change scenarios, total biogenic volatile organic compounds (BVOC) emissions will exhibit pronounced variability, predominantly sourced from plants and wildfires. These natural emissions remain largely uncontrollable, as their dynamics are governed by ecological and climatic factors, rendering policy interventions largely ineffective. Although anthropogenic sources are subject to regulation,

they fail to mitigate the complexity introduced by natural emissions. The interplay between natural and BVOC emissions exerts an intricate influence on air quality, necessitating a comprehensive, integrated approach to enhance air quality management. Moreover, we acknowledge that we adopt CAM4 model in our simulation, without using the latest CAM5. We also want to point out the limitations of using the bulk aerosol scheme in our current model configuration which could cause large differences in the tropical tropospheric hydroxyl radical and then thus the tropospheric ozone and aerosol burden. For further studies, we recommend the use of the latest MAM mechanisms for the aerosol schemes.

Methods

Integrated modeling framework

An integrated modeling framework is established to estimate the air quality and health co-benefits under climate change mitigation (Fig. 6). The integrated framework includes a global energy-economy model (AIM/CGE), an air quality model (CAM-chem), and a health impact assessment model (IMED|HEL). The AIM/CGE model simulates the pathways of economic development, industry output, energy consumption, and the emissions of greenhouse gases (GHGs) and air pollutants. The future-year emission inventory in line with each scenario is downscaled and fed into the CAM-chem model to estimate the corresponding PM_{2.5} and ozone concentrations. The IMED|HEL model estimates the health impacts of different diseases and premature mortality from ambient PM_{2.5} and ozone pollution.

AIM/CGE model description

AIM/CGE is a global computable general equilibrium model developed by Japan's National Institute of Environmental Studies (NIES) for a comprehensive assessment of climate change at global and regional scales. As the core part of the AIM (Asia-Pacific integrated assessment model) model, it can simulate equilibrium economic status by solving a series of market-clearing functions such as production factors, products, foreign exchange, etc. It can reflect the interdependence and interaction between multiple sectors and markets^{26–28}. Operating in a recursive-dynamic way, this model analyzes how the economic and energy systems unfold under assumptions of future economic development and target fiscal policies or specific climate policies. In this study, the AIM/CGE model provides projections of sectoral and regional economic activities, energy consumption, and emissions of GHGs and air pollutants from 2005 (the base year) to 2100. The regional emissions results in each scenario are then downscaled to generate the gridded emission inventories²⁹.

Air quality modeling

The global PM_{2.5} and ozone concentrations under each scenario and in each studied year are simulated by the state-of-the-art global air quality model CAM-chem, which is based on the global Community Atmosphere Model (CAM) version 4, the atmospheric component of the Community Earth System Model (CESM, v1.2.2)^{30,31}. The model uses a horizontal grid with a resolution of 2.5° × 1.9° (longitude × latitude) and 56 vertical levels between the surface and 4 hPa (≈40 km) with a time step of the 1800s. To be consistent with the spatial resolution, primary emission inventories with 0.5° × 0.5° resolution downscaled from regional emissions generated by the AIM/CGE model are re-gridded to fed into the CAM-chem model. The NASA Global Modeling and Assimilation Office GEOS-5 meteorology is used to drive the climate conditions in the model. For all the simulations, we run CAM-chem for 11 consecutive years from 2008–2018, and the rest 10-year average for data analysis. By applying the same historical meteorology for all the simulations, we neglect the possible ozone changes caused by the changing climate^{32,33}. For all the simulations, we apply the same historical meteorology from 2008 to 2018 to eliminate future climate changes caused by climate policy in China on air quality. Chemically

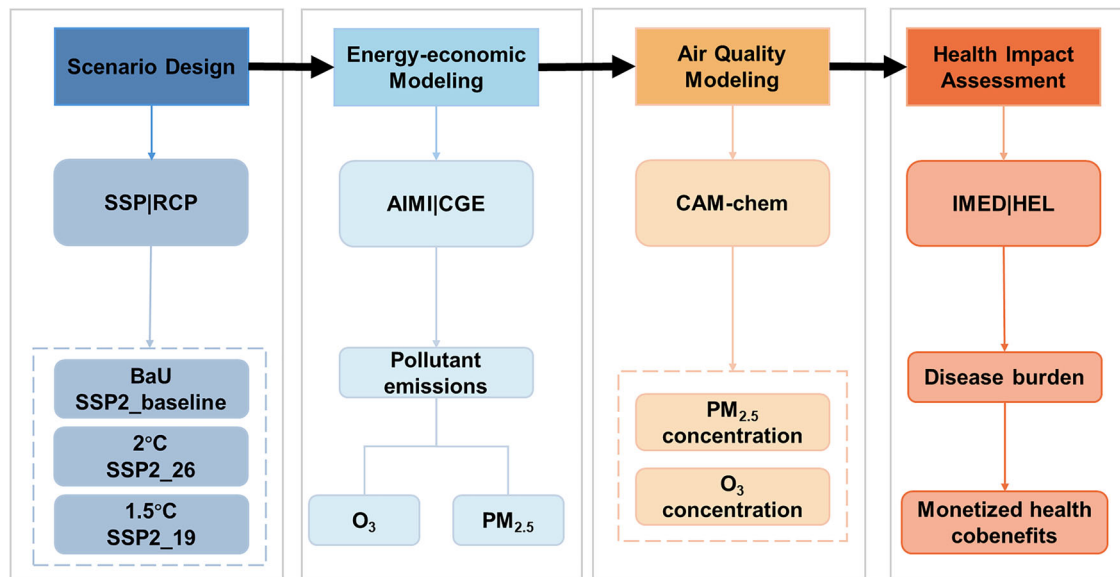


Fig. 6 | Research Framework. The integrated framework includes a global energy-economy model (AIM/CGE, Asia-Pacific Integrated Model/Computable General Equilibrium), an air quality model (CAM-chem, Community Atmosphere Model

with Chemistry), and a health impact assessment model (IMED | HEL, Integrated Model of Energy, Environment and Economy for Sustainable Development | Health module).

active stratospheric species (such as Ozone, NO, NO₂ and N₂O₅) are prescribed as monthly mean distribution using the climatology from the Whole Atmospheric Community Climate Model simulations^{30,34}. Monthly temporal variations for the anthropogenic air pollutants are added by using the monthly emission factors from REanalysis of the TROpospheric chemical composition (RETRO).

The choice between regridding and downscaling is pivotal in atmospheric modeling, particularly for exposure assessments involving fine-scale pollution features. While downscaling integrates higher-resolution data to capture localized emission hotspots, regridding redistributes coarse-grid data without adding new fine-scale information. Our study employs regridding instead of downscaling, given the absence of reliable future-oriented, fine-scale emissions data across multiple sectors. Although previous studies^{35,36} demonstrated the benefits of downscaling for historical data, their methods rely on detailed, spatially resolved data unavailable for long-term projections. Furthermore, Pungler and West (2013) caution that indiscriminate downscaling may introduce new biases, particularly when applying historical spatial distributions to future scenarios with evolving emission patterns³⁷. Thus, our approach prioritizes consistency in sectoral representation and reduces uncertainties associated with speculative fine-scale data, aligning with Pungler and West's recommended grid scale for global, multi-sector analyses. More detailed discussions could be found in Supplementary Method 2.

The monthly emission factors from REanalysis of the RETRO over the past 40-year global emissions dataset³⁸. The Non-Methane Volatile Organic Compounds (NMVOCs) are re-specified into CAM-chem chemical speciation^{34,39–43}, following the discussion by the CAM-chem model⁴⁴. The Model of Emissions of Gases and Aerosols from Nature (MEGAN-v2.1⁴⁵) simulates biogenic emissions for 150 compounds online within CAM-chem. Lightning NO_x emissions are calculated online with 3.21 TgN yr⁻¹ (five-year average), which is lower than the average simulated from the ACCMIP models for 2000, but within the range (5 ± 3 Tg N⁻¹⁴⁶. Other natural emissions (soil, ocean, and volcano) are from the standard CAM-chem emission files³⁰, and remain the same for all simulations⁴⁷. However, such underestimates may not noticeably influence our main conclusions since we focus on the co-benefits of different climate policies on ozone changes. CAM-chem model

employed the MOZART chemical mechanism and bulk aerosol module as described in Tilmes et al. (2016)⁴⁸. In this version of aerosol module, the sulfate aerosol is formed through the oxidation of SO₂ and in both the gas and aqueous phases. Secondary organic aerosols (SOAs) are derived using the two-product model approach, with laboratory-derived yields for monoterpenes, isoprene, and aromatic photo-oxidation. Moreover, the simulated PM_{2.5} concentrations are calculated as the sum of SO₄ + NO₃ + NH₄ + OC + BC + SOA + 0.1*Dust + 0.25*Sea salt⁴⁹.

CAM5 model incorporates recent advancements in aerosol modules and is considered more accurate for simulating aerosols within the CAM-Chem framework^{47–49}. Our study opted to utilize the CAM4 model for several critical reasons. Tilmes et al. (2015) demonstrated that differences in tropospheric aerosol surface area between CAM4 and CAM5 significantly influence the tropical tropospheric hydroxyl radical (OH) burden, resulting in a substantial half-year discrepancy in tropical methane lifetime estimates⁵⁰. Despite these improvements, the CAM4 model remains adopted and validated in the research community⁵¹, providing a robust reference framework for our analysis. Moreover, our study primarily focuses on the relative differences in simulated global concentrations between baseline and future scenarios. By emphasizing these relative changes, we aim to mitigate potential uncertainties associated with aerosol representation, thereby preserving the integrity of our comparative analysis.

Exposure assessment

To assess the population exposure levels, population-weighted PM_{2.5} or ozone concentrations in different countries or aggregated world regions are quantified by overlapping the gridded global concentration results with the historical and projected future gridded population maps in the consistent years. The estimated PM_{2.5} or ozone concentrations with a spatial resolution of 2.5° × 1.9° from the CAM-chem model are further downscaled to 0.5° × 0.5° using the area-reserve interpolation method. The 0.5° × 0.5° global population data are prepared by upscaling the 0.125°-resolution gridded data from the SEDAC database in different SSPs. The exposure levels are then compared with the AQGs⁵² to assess the attainment of or the deviation from the air quality standard.

Health impact assessment

IMED | HEL quantifies global and regional health impacts due to PM_{2.5} and ozone pollution using the up-to-date exposure-response functions (ERF), which describe the epidemiology linkages between relative risk (R.R.) of morbidity, mortality, or work-loss rates and pollution concentration. By using the ERFs, we evaluate the excess mortality rates for adults by multiplying the baseline mortality rates with the population attributable fraction (PAF) of excess mortality or morbidity derived from R.R. For premature mortality induced by PM_{2.5} pollution, we adopt three different types of ERFs: log-linear, IER, and GEMM models to address the potential uncertainties in health impact assessment from the forms and parameters of the ERF functions. The results from the GEMM model are presented in the main text, while the results from the other two ERFs are regarded as sensitivity analysis. For ozone pollution, the epidemiological evidence is more abundant than PM_{2.5}, and a log-linear model indicated in an epidemiological study³³ was applied. For more settings about the IMED | HEL model, refer to our previous studies^{11,25,54–60}.

Cost and benefit analysis

We further monetize the health impacts with the Cost of Illness for morbidity and willingness-to-pay (WTP) method for mortality, in which the loss of life value due to mortality is estimated using the VSL (value of a statistical life) parameter. Additional health expenditures are calculated by multiplying the outpatient and hospital admission prices by the total endpoints. The price is a function of the per capita GDP of each province, and the parameters β and θ are estimated through regression analysis of the statistical price by disease and GDP of each province from 2003 to 2012. Additional medical expenditures are treated as household expenditure pattern changes, suggesting that the more money spent on health services, the less on other goods.

We consider the variant of VSL values by region and year in an elasticity relationship with the heterogeneous per capita GDP in different countries and future years. Considering the global coverage of this study, we calculate the VSL values for the countries in two different income groups separately. For regions in upper-middle or high-income countries defined by the World Bank, we use a baseline VSL from a study in China⁶¹ and an income elasticity of 1.2, while for the middle or lower-income countries, we use a baseline VSL from a study in OECD⁶² and the recommended VSL income elasticity of 0.8 (Supplementary Table 4). Total VSL losses in each country are quantified by multiplying the total pollution-induced premature mortality by the corresponding estimated VSL values in this country in specific years. Comparing these co-benefits with the GDP losses due to carbon mitigation indicated by the AIM/CGE model, the cost and benefit ratios for the SSP2_26 and SSP2_19 scenarios are contrasted.

Scenario design

A series of scenarios are designed with two dimensions to understand air pollution and human health co-benefits under different levels of carbon mitigation pathways. The SSPs depict five global futures (SSP1-5) with substantially different socio-economic conditions. SSP2 describes medium challenges of both kinds and represents a future that follows middle-of-the-road pathways. Additional climate mitigation runs have been developed for each SSP baseline, including additional long-term radiative forcing targets representative concentration pathways (RCPs) of 1.9, 2.6, 4.5 and 6.0 W/m² in 2100. Pollution control targets, which we specify relative to those in current OECD countries. The speed at which developing countries ‘catch up’ with these levels and the effectiveness of policies in current OECD countries. The pathways for pollution control technologies, including the technological frontier, represent best practice values at a given time. This study assesses the SSP2 as the central socio-economic condition representing the baseline trend^{63,64}. The reference climate scenarios (SSP2_baseline) assume pathways without

carbon constraints, while the two mitigation scenarios are 2 °C or 1.5 °C climate target⁶⁵. More detailed information about scenarios can be found in the Support Information⁶⁶.

Reporting summary

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

Data availability

Main data supporting the findings of this study are available within the Manuscript and Supplementary Information. Source data underlying figures in the Manuscript are provided within the Source Data. Source data are provided with this paper.

Code availability

The code base of the IMED model has been developed at Peking University and related code used in this study is available from the first author Yang Xie (xieyangdaisy@buaa.edu.cn) upon request. AIM/CGE model has been developed by AIM team and related code used in this study is available from co-author Prof. Shinichiro Fujimori (fujimori.shinichiro.8a@kyoto-u.ac.jp). CAM-chem mode code is available from Prof. Yuqiang Zhang (yuqiangzhang.thu@gmail.com).

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Competing interests

The authors declare no competing interests.

Additional information

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Author contributions

Y.X. designed the study and performed the data analysis; B.C. provided supervision. Y.X. wrote the paper; S.F., Z.L., Y.Z., and B.C. provided

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