Pathways to a healthy net-zero future: report of the *Lancet* Pathfinder Commission

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Executive summary

Deep, rapid cuts in greenhouse gas emissions are needed to limit future global temperature increases to 1·5°C above pre-industrial levels, but current progress is inadequate to achieve the goals of the Paris Climate Agreement and to reduce future risks from climate change. Many actions to mitigate greenhouse gas emissions can also deliver near-term health co-benefits, for example from reduced air pollution, consumption of healthy diets, and increased physical activity. High-quality evidence on the type and magnitude of co-benefits that can be realised and improved knowledge of how to promote the implementation of such actions can support progress towards net-zero greenhouse gas emissions by 2050. The *Lancet* Pathfinder Commission was established to collate and assess the evidence on the near-term health effects of greenhouse gas mitigation, including both modelling studies and evaluated implemented actions. The Commission's aim is to assess the potential and achieved magnitude of the benefits for health and climate of different mitigation actions and, where possible, the factors facilitating or impeding implementation.

An umbrella review of relevant systematic reviews was conducted across multiple peer-reviewed literature databases, identifying 6902 records, of which 317 full texts were screened. From the full text screening, 26 reviews presented quantitative estimates of both changes in greenhouse gas emissions and health outcomes. 200 mitigation actions were identified across all sectors, of which 178 (89%) presented modelled estimates of the effects of climate mitigation actions on greenhouse gas emissions and health across different sectors and scales. We converted mitigation actions to CO_2 equivalents (CO_2eq) to allow the inclusion of other greenhouse gases alongside CO_2. We quantified health outcomes in terms of health co-impact intensity (an increase or decrease in years of life lost [YLL] per 100 000 population per year) and climate benefits as carbon mitigation intensity (kilotonnes of CO_2eq per 100 000 population per year).

Major benefits to health are delivered through reductions in air pollution, consumption of healthy sustainable diets, and the promotion of active travel and public transport. Clean cookstoves had the greatest estimated median health co-benefit (a reduction of 1279 YLL per 100 000 population per year, based on data from India), followed by dietary changes (306 YLL per 100 000 population per year). Actions in the transportation sector resulted in a median reduction of 60 YLL per 100 000 population per year. In the electricity generation sector, we estimated a median reduction of 11 YLL per 100 000 population per year, with some evidence for larger benefits in India (a reduction of 149 YLL per 100 000 population per year for the single reported study). Actions to decarbonise electricity generation generally had the greatest carbon mitigation intensity of actions in a single sector (a median estimated reduction of 171 kilotonnes of CO_2eq per 100 000 population per year). Multisectoral actions might achieve very high mitigation intensity, but their effects were highly variable, depending on the country context. Although global modelling studies show potential large benefits to health from reductions in ambient air pollution, these are not currently reflected in the data within systematic reviews which tend to feature small-scale actions with limited benefits.

We searched peer-reviewed and grey literature to further identify examples of implemented actions that had measured and reported both emission reductions and health co-impacts. These examples provide evidence on the realities of implementing mitigation actions in different geographical locations and socioeconomic settings, and at a variety of spatial scales. The search included relevant articles from the Pathfinder umbrella review and from a recent systematic mapping exercise, which used machine learning to classify peer-reviewed research papers on climate and health. In addition, pre-existing databases from C40 Cities and CDP (formerly the Carbon Disclosure Project) were screened, alongside studies submitted in response to a call for evidence published in *The Lancet*. Further targeted searches were carried out for actions with a focus on the enhancement of natural or modified ecosystems to deliver climate and biodiversity benefits (ie, nature-based solutions). A list of all evaluated actions submitted through the call for evidence is given in the appendix (pp 7–9).

Examples of implemented actions with exemplary stakeholder engagement and inclusion were identified. These actions have the potential for significant wins for the environment and human health if taken up at scale, including building retrofitting in Australia, deployment of incentives and policies for the adoption of renewable energy in the USA, and the provision of health-care services to communities in Indonesia to incentivise the preservation and restoration of forests. There is an

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Key messages

- An abundance of modelled evidence attests to the health co-benefits of climate mitigation action across many sectors of society. Increased ambition is urgently needed to accelerate progress and achieve the health co-benefits from a just transition to a net-zero emissions future.
- Health co-benefits are additional to the benefits gained from reducing the impacts of climate change on health. Co-benefits are delivered through key pathways, such as reductions in air pollution from replacing fossil fuels with clean, renewable energy sources; consumption of healthy, sustainable diets; and the promotion of active travel and use of public transport.
- To capitalise on these additional health gains, while reducing inequities and meeting climate targets, health co-benefits must be incorporated into the delivery of the Paris Climate Agreement including through nationally determined contributions and long-term low greenhouse gas emission development strategies.
- Improved monitoring of progress alongside better harmonised research can support ambitious climate action. A greater emphasis must be placed on estimating the magnitude of both the health and greenhouse gas effects of implemented mitigation actions, including through processes such as the Global Stocktake. Future research should use consistent methods and descriptions of objectives, settings, and assumptions to support informed decision making and inclusion in national and global policy. Integrated evaluation of actions can also ensure implementation achieves equitable delivery of benefits and minimises trade-offs.
- Systems approaches are needed; achievement of transformative change across sectors to achieve improved health equity at net-zero greenhouse gas emissions requires systems approaches that integrate adaptation and mitigation and address underlying structures driving inequity and rising greenhouse gas emissions. Examples of implemented and evaluated transformative action are urgently needed to inspire and inform change.
- A coalition of organisations, and subnational and national initiatives, is proposed to accelerate progress towards net-zero greenhouse gas emissions and improve health, with a commitment to monitor and evaluate effects on health and greenhouse gas emissions as well as to share experiences about successes and failures.

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urgent need for further prospective studies of climate actions in diverse settings and contexts, to evaluate the impact of implemented policies on greenhouse gas emissions, health-related exposures, and mental and physical health outcomes. Monitoring and measurement are needed in all settings, but a focus on improving data availability from low-income and middle-income countries could help to inform and promote a just and equitable transition to net zero including universal access to clean renewable energy. High-quality evidence on integrated approaches that achieve synergies between climate mitigation and adaptation actions where possible, and avoid maladaptation and trade-offs, can help prevent increased inequity from poorly designed policies. Identified trade-offs include unemployment from unplanned transition from fossil fuels to renewable energy and increased exposure to household air pollution from reduced ventilation following draught proofing and insulation.

The urgency of accelerating climate change mitigation to achieve the goals of the Paris Climate Agreement suggests that there is a need for new approaches to scaling up ambitious action, particularly focusing on the systemic drivers of greenhouse gas emissions (including addressing inequitable and unsustainable patterns of consumption, particularly in high-income settings). The full integration of health co-benefits and equity considerations into the delivery of the Paris Climate Agreement including through nationally determined contributions (NDCs) and long-term low greenhouse gas emission development strategies can maximise health gains and minimise trade-offs, while reducing inequity, promoting efficient use of resources, and meeting climate targets.

Modelled evidence from the umbrella review shows that some actions might deliver large benefits for health with only small benefits for climate mitigation and vice versa, whereas some actions have the potential to deliver significant wins for the environment and health. The magnitude of the benefits depends not only on the intensity of their effects but also on the extent to which they are implemented at scale. A judicious mix of actions is needed to deliver benefits for both outcomes. Implemented examples showcasing the benefits of a systems approach to address efficient resource use alongside demand reduction by tackling drivers of unsustainable behaviours in resource use could help to persuade decision makers and the public of the utility of such an approach.

The recommendations of the Commission include the formation of a coalition of actors—including cities, subnational and national governments, non-governmental organisations, and institutions that are committed to rapid climate action—to achieve the goals of the Paris Climate Agreement. The coalition would undertake monitoring, evaluating, and communication of the impacts of their actions on health and greenhouse gas emissions to foster mutual learning and tackle some of the key challenges outlined in this report. The Commission also advocates the development of systems approaches that incorporate health into climate mitigation policies (including the NDCs under the Paris Climate Agreement) and integrate mitigation and adaptation actions where feasible. The use of standard metrics for evaluating the climate and health impacts of mitigation actions and the development of living reviews to continuously update evidence on effective actions are also recommended.

Introduction

Urgent cuts in greenhouse gas emissions are needed to limit future global temperature increases to 1·5°C above pre-industrial levels (or, failing that, to well under 2°C), the goal of the Paris Climate Agreement.[1,2] Climate change has been described by WHO as the greatest threat to human health and can impact health through a range of pathways, both direct and indirect.[3] Despite a growing awareness of the challenges we face and the severity of climate impacts, there is still a large gap between projected emission trajectories and the size

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and speed of the emission reductions needed to achieve the goals of the Paris Climate Agreement.[2,4,5] In many sectors, the continued—and, in some cases, increasing—dependence on fossil fuels is impeding progress towards a net-zero-emission, climate-neutral future.

Many policies to reduce greenhouse gas emissions result in near-term health co-benefits (ancillary benefits), in addition to reducing the risks to health from climate change.[6,7] Capitalising on these co-benefits can provide a powerful incentive for more ambitious climate action. Emphasising the benefits of action, in addition to the risks to humanity posed by inaction, provides an alternative narrative to climate fatalism, fuelled by the perception that change is too difficult and too costly to succeed. A predominantly negative discourse on climate change might accentuate polarisation and impede progress, whereas a focus on the opportunities for transformative change to an economy that supports health and equity within planetary boundaries can provide hope and a compelling vision of an inclusive and sustainable future.[8,9] Communicating the wider co-benefits of climate mitigation can help engage more diverse audiences and build support for change.[10] Much action on climate mitigation has, to date, focused on supply-side solutions that improve efficiency or provide technical solutions to current demands (eg, increased provision of solar and wind energy) and carbon dioxide (CO_2) removal, but recent analyses have emphasised the need for additional demand-side strategies, particularly in high-emitting countries,[11,12] and a focus on co-benefits can help reframe action to take a systems approach. Although human health is among the most well evidenced co-benefits of mitigation actions, uncertainties exist about the magnitude of these mitigation actions in different contexts and how to implement such actions at scale.[11,13–15]

The scope of the Commission report

The Pathfinder Commission[16] was established to assess the evidence on the health co-benefits of greenhouse gas mitigation policies, both modelled and implemented, and to synthesise evidence on the development and implementation of actions across a range of sectors, to improve and sustain health while accelerating progress towards a net-zero future. It aims to fill key knowledge gaps to optimise action and increase progress—namely, which actions will have the largest multiple benefits (and will be the least subject to trade-offs) for health and the environment in particular contexts, and which implementation strategies should be employed for effective scale-up. The Commission's objectives are to (1) map the pathways linking mitigation actions with health and assess the magnitude of potential health co-benefits and greenhouse gas mitigation impacts through the synthesis of evidence (umbrella review),[17] and (2) investigate and analyse evaluated examples of implemented greenhouse gas mitigation actions and, where possible, understand the reasons for success or failure of such actions.[18] This report presents the findings on the health co-benefits of greenhouse gas mitigation by sector from an umbrella review (a review of systematic reviews) and gives summaries of evaluated examples of implemented actions (case studies). Both encompass a wide range of sectoral and intersectoral initiatives in energy, transport, the built environment (including cities), agrifood systems (including agriculture), industry, sanitation, and nature-based solutions.

Actions taken to adapt to climate change that integrate mitigation are also considered within scope. For example, modification of building design to enhance passive cooling, reducing heat exposure and thus reducing energy use due to decreased need for air conditioning, is included, whereas standalone adaptation activities, even those with links to health (such as early-warning

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See **Online** for appendix

Panel 1: Links with the *Lancet* Countdown on health and climate change

Lancet Countdown is an international academic collaboration that brings together more than 200 researchers from every continent (including multiple members of the Pathfinder Initiative) to monitor the changing links between health and climate change. Through annual iterations of more than 40 indicators, it tracks progress towards five key domains:

1 The health impacts, exposures, and vulnerabilities of climate change.
2 Adaptation, planning, and resilience for health.
3 Mitigation actions and their health co-benefits.
4 Economic and financial aspects of the interaction between climate change and health.
5 Public and political engagement in climate change and health.

Lancet Countdown's work to measure indicators relevant to the health co-benefits of climate mitigation draws on multiple databases and regularly updated methodologies to produce annual estimates, such as on the provision of clean household energy, premature mortality from air pollution by sector and exposure to indoor air pollution, sustainable transport and agriculture for food production, and health-care decarbonisation. The Pathfinder Initiative builds on that work by quantifying the wider evidence base for climate mitigation actions with health co-benefits, understanding patterns in the underlying evidence base and the context and methodologies behind estimates of co-impacts (including the trade-offs and synergies between actions), assessing the implementation status of proposed actions, and sharing case studies. Wherever possible, the evidence produced by the Pathfinder Initiative will be used to refine and advance the *Lancet* Countdown's indicators, while Pathfinder will, where appropriate, build on *Lancet* Countdown's methodologies and data to refine its own assessments.

For more on the ***Lancet* Commission on sustainability in health care** see https://ysph.yale.edu/yale-center-on-climate-change-and-health/healthcare-sustainability-and-public-health/lancet-commission-on-sustainable-health-care/

For the report of the **WHO Council on Economics of Health for All** see https://www.who.int/publications/i/item/9789240080973

systems), are excluded. The report acknowledges but does not focus on the health effects of climate change. Reducing climate change-related risks provides additional health benefits to the health co-benefits of greenhouse gas mitigation actions that are the focus of this report. Some exemplary implemented actions to reduce greenhouse gas emissions were identified within the health-care sector but, as these do not measure health exposures or outcomes, they are outside the scope of this report. A separate summary of these findings will be published and will feed into the work of the recently established *Lancet* Commission on sustainability in health care. The Pathfinder Commission also builds on the work of several previous *Lancet* series and commissions,[7,8,19–21] including the *Lancet* Countdown on health and climate change (panel 1).[22]

Issues of global justice are core to achieving a just and equitable transition and to delivering health co-benefits to those most in need (panel 2).[28] The Commission report acknowledges the work of the WHO Council on the Economics of Health for All in highlighting that the economy is generating poor climate and health outcomes,

Panel 2: Challenges for achieving a just and equitable transition to net zero

The inequalities in per-capita emissions are stark. At the global level, the top 10% of global emitters (771 million individuals) are estimated to be responsible, on average, for 31 tonnes of CO_2 per person per year, amounting to about 48% of global CO_2 emissions. The lowest 50% of emitters (3·8 billion individuals) emit, on average, 1·6 tonnes and were responsible for around 12% of all emissions in 2019. Even more strikingly, the top 1% emit on average 101 tonnes CO_2 equivalents per person per year and contribute around 17% of all annual emissions.[23] Effective policies must address profound inequalities in historical and current emissions by bringing down the emissions of the highest emitters as a priority, while ensuring the needs of all are satisfactorily met, including universal access to clean renewable energy, which might mean increased consumption by those in areas with currently low emissions.[24] Depending on how health benefits are valued by society, keeping global temperature rises to well under 2°C might confer many economic benefits that offset, or even exceed, the cost of mitigation efforts. One assessment suggested that regions and nations that have contributed historically to high fossil fuel-related emissions (eg, the USA, Europe, and Japan) implement deep cuts in greenhouse gas emissions, primarily for reasons of global efficiency or climate justice, while other nations (eg, India and China) act primarily to capitalise on health co-benefits.[25] In practice, nations are likely to act from a range of motivations, including near-term and long-term self-interests as well as a desire to show political leadership. Several nations have been able to achieve long healthy life expectancy at fairly low environmental footprints (appendix p 30).[26] The policies and procedures implemented in these nations could help to guide equitable climate action and the lessons from their relative success should be assessed.[27]

Vulnerability to the impacts of climate change is closely linked to gender inequality, and so addressing this inequity can promote increased resilience for disadvantaged populations while making progress on global development and climate goals.[28] Key to a just and equitable transition will be to ensure that the co-benefits delivered by climate mitigation action are fully accessible to all, including women and minority groups. Vulnerable populations have additional concerns when it comes to the spillovers of some climate mitigation actions. There is a growing body of evidence outlining how marginalised and vulnerable populations are at greatest risk of climate breakdown.[29] Less frequently considered is how systematic discrimination can translate into unintended negative impacts of climate mitigation actions specific to those groups, exacerbating existing inequities and deepening injustices.[29] Policies must ensure that marginalised and vulnerable populations are protected and account for unintended consequences. For example, the Net Zero Emissions by 2050 scenario by the International Energy Agency estimates that demand for critical minerals, which form essential components of many forms of clean energy, such as electric vehicles and battery storage, will increase by 3·5 times by 2030.[30] The increased demand for these minerals presents several challenges, including the lack of governance to manage the environmental, social, and economic impacts from their mining and the absence of support for developing economies to ensure that their mineral wealth delivers equitable benefits to local communities. There are increasing calls for an international framework for dialogue and policy coordination among producers and consumers of critical minerals to ensure sustainability, transparency, and equity in the shift to net zero.[31]

For example, when designing and implementing fossil fuel phase-out policies, a balance between a fast decarbonisation and a just and equitable transition for workers is required.[32] Due to large-scale phasing out of coal plants across Europe, the USA, and China, more than 4 million coal workers have lost their jobs.[33] Coal mining communities are often characterised by geographical isolation and strong identities, which make a just and equitable transition to alternative employment challenging. The loss also impacts other sectors, including retail or social services.[33] Therefore, a shift to renewable energies has profound impacts on coal mine workers and communities, although such impacts are not always evenly distributed.[34] For example, coal mine workers employed by state-owned companies in China were provided with relocation and retirement plans, whereas workers from private mine companies were made redundant without assistance or adequate compensation.[34] Therefore, the negative consequences for employees can be avoided through adequate compensation, assistance, and re-training, and the shift to renewable energies can further provide an opportunity for societies to overcome existing inequalities.[35]

with a disproportionate impact on certain regions and people, by design, and that economic policy must therefore change in order to prioritise the interlinked goals of health, climate, and equity. A comprehensive review of the equity implications of climate mitigation policies is currently underway for the WHO World Report on Social Determinants of Health Equity, entitled *Climate Change and Heath Equity*. The scope of their work is to provide analysis and evidence on the impacts of climate change on health equity and examine the trade-offs between action on climate change and action on the social determinants of health equity, to inform required actions that both address climate change and health inequities. We aim to add value to their work without duplicating effort.

The *Lancet* Pathfinder Commission is a core part of the wider Pathfinder Initiative that aims to communicate its findings to a range of decision makers in sectors contributing large proportions of greenhouse gas emissions, varying by country and level of development. Partner organisations comprise the C40 Cities network, CDP (formerly the Carbon Disclosure Project), the Organisation for Economic Co-operation and Development (OECD), the UN Sustainable Development Solutions Network (SDSN), and the Alliance for Health Policy and Systems Research.

Pathways to net zero alongside improved public health

The challenge of achieving net-zero emissions by 2050 at the latest presents a unique opportunity to drive transformative changes in all sectors of society (figure 1). Three major pathways by which climate change mitigation actions can yield health co-benefits are: (1) the reduction of air pollution, particularly particulate matter with a diameter of <2·5 μm ($PM_{2\cdot5}$; eg, black carbon, nitrogen dioxide [NO_2], and tropospheric ozone [O_3]) from phasing out fossil fuels by replacing them with clean renewable energy and addressing other sources of greenhouse gas emissions that co-emit air pollutants or their precursors; (2) increased consumption of healthy, sustainable diets; and (3) increased physical activity from active travel (walking and cycling) and the use of public transport.

The potential magnitude of health co-benefits is impressive, amounting to millions of premature deaths prevented worldwide for each pathway. Modelled estimates of the nationally determined contributions (NDCs) of greenhouse gas emission reductions in just

For more on the **WHO World Report on Social Determinants of Health Equity: Climate Change and Health Equity** see https://www.who.int/initiatives/action-on-the-social-determinants-of-health-for-advancing-equity/world-report-on-social-determinants-of-health-equity

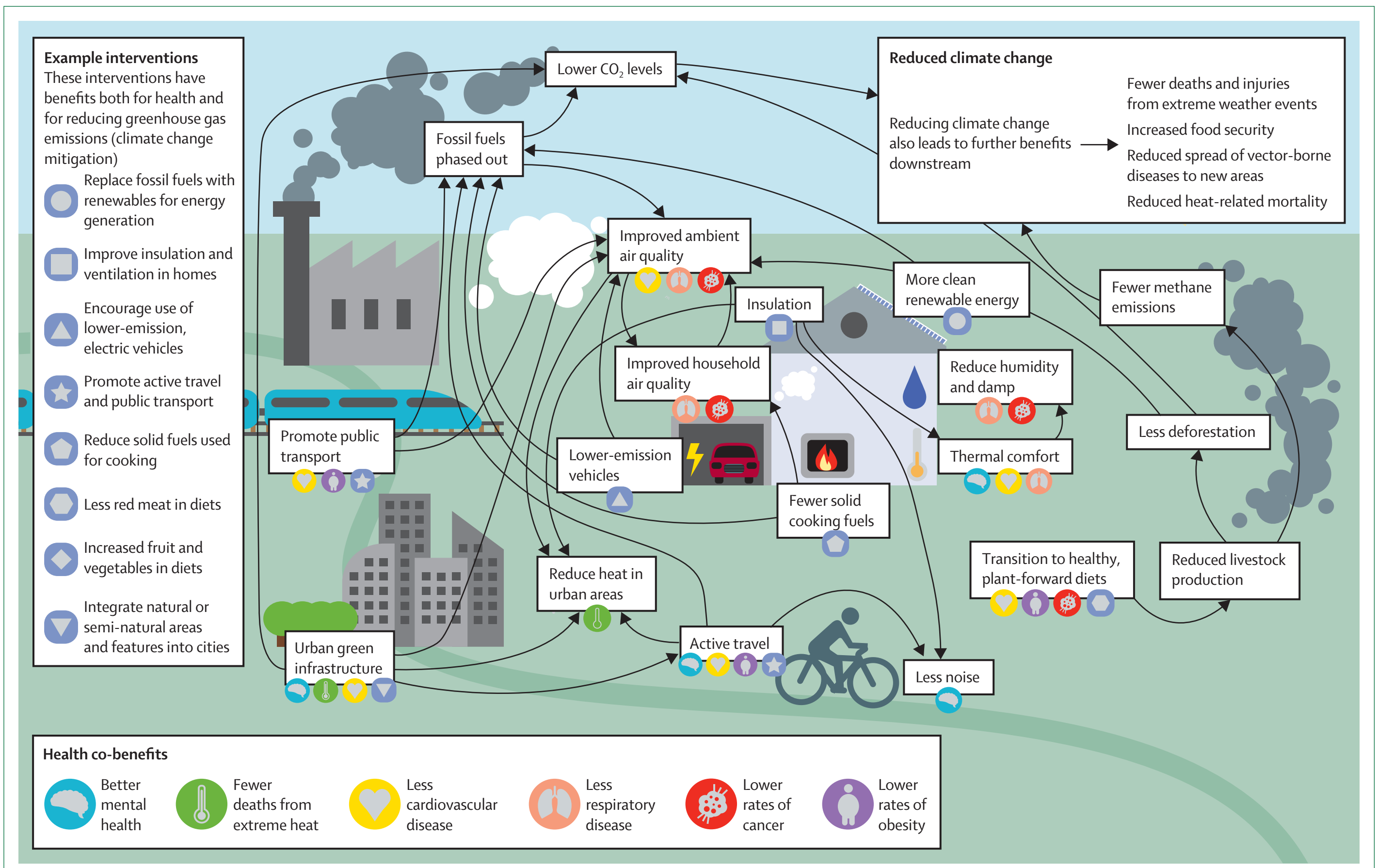

Figure 1: **Key pathways and connections between climate mitigation actions and health**

nine countries showed that, compared with the current pathways scenario, the sustainable pathways scenario resulted in an estimated annual reduction by 2040 of about 1·18 million air pollution-related premature deaths, 5·86 million diet-related premature deaths, and 1·15 million premature deaths due to physical inactivity, with some overlap between them. Adopting a more ambitious scenario that emphasises health benefits in all climate policies would result in substantial additional estimated reductions of premature deaths.[36] The near-term health co-benefits of mitigation are in addition to the health benefits of keeping global mean temperature rises to as near to 1·5°C as possible that will also avert many projected deaths from climate change.[37,38]

Air pollution

On a global scale, the estimates of annual, fossil fuel-related, ambient air pollution deaths range from the Global Burden of Diseases, Injuries, and Risk Factors Study (GBD) estimate of just over a million,[39] based on a small number of specific health outcomes, to other estimates of 3·6 million[40] and up to 8·7 million annual premature deaths,[41] with the latter having very wide uncertainties. Air pollution co-benefits are largely due to reductions in $PM_{2·5}$ resulting in reduced risks of common non-communicable diseases, including ischaemic heart disease, stroke, diabetes, chronic obstructive pulmonary disease (COPD), lung cancer, and acute respiratory infections. This implies that major health benefits will result from replacing fossil fuels with clean, renewable energy sources. Such health co-benefits would occur predominantly in Asia due to exposure of increasingly ageing populations to current high concentrations of fossil fuel-related air pollution. However, benefits are appreciable in other regions because even low amounts of air pollution are harmful.[40,42,43] Ambient air pollution is increasing across Africa. In the absence of deliberate intervention, it will increase morbidity and mortality, diminish economic productivity, and undercut development. Because most African countries have a far lower level of energy use per capita than their high-emitting counterparts, they have opportunities to undertake a just and equitable transition to wind and solar energy, avoiding a reliance on fossil fuel-based economies and minimising pollution.[44] Major additional benefits would result from reduced household air pollution, largely in low-income countries.[45]

Short-lived climate pollutants, such as tropospheric O_3 and black carbon, are hazardous air pollutants responsible for many premature deaths. About 50% of black carbon emissions arise from household sources and about 25% from transportation. A study identified 14 key measures targeting methane (CH_4; a precursor of O_3) and black carbon emissions that, if implemented, would reduce the projected global mean temperature increase by about 0·5°C by 2050. If properly utilised, these measures were also projected to prevent 0·7–4·7 million annual premature deaths from ambient air pollution and increase crop yields by 30–135 megatonnes (ie, million tonnes) annually from O_3 reductions in 2030 and beyond.[46] The Global Methane Assessment shows that CH_4 emissions from human activities can be reduced by up to 45% this decade, thus avoiding almost 0·3°C of global warming by 2045, consistent with the Paris Climate Agreement's goal to limit global temperature rise to 1·5°C. A 45% reduction would prevent an estimated 260 000 premature deaths from tropospheric O_3, 775 000 asthma-related hospital visits, 73 billion hours of lost labour from extreme heat, and 25 megatonnes (million tonnes) of crop losses annually.[47]

A worsening cycle of climate–fire feedback might also increase emissions and negatively impact health. Fire emissions from global forest ecosystems have been increasing since 2000, and increasing numbers of boreal fires and stronger climate–fire feedbacks challenge climate mitigation efforts.[48] The global mortality burden associated with wildfire smoke was estimated to be between 260 000 and 600 000 in 2012,[49] but this range could be an underestimate due to increased fire occurrences in heavily populated parts of the world.[50]

Healthy sustainable diets

Systematic reviews have shown the health and greenhouse gas benefits of predominantly plant-based diets for adult populations.[51] The EAT-*Lancet* Commission estimated that about 10–11 million premature deaths from non-communicable diseases could be prevented annually worldwide by 2040 if the so-called planetary health diet (characterised by high consumption of plant-based foods and low intake of red meat and dairy products) was widely consumed.[20] Ensuring that such dietary choices are affordable, particularly in low-income and middle-income countries (LMICs), is a major challenge.[52]

Active travel

Physical inactivity is a major risk factor for non-communicable diseases and has been estimated to be responsible for about 5 million premature deaths worldwide annually.[53] Population-attributable risks were more than double in high-income countries compared with low-income countries, although 69% of total deaths and 74% of cardiovascular disease deaths associated with physical inactivity occur in middle-income countries due to their population size.[54] Active travel and increased use of public transport offer the most feasible and cost-effective route to increasing population levels of physical activity, particularly in urban settings.[55,56] Additional health benefits could arise from reduced road traffic injuries and noise pollution if integrated policies were implemented.[57]

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Other health co-benefits

Mitigation actions such as nature-based solutions, including forest protection, agroforestry, and land restoration,[58] are likely to offer significant opportunities to sequester and store carbon but quantitative estimates of health benefits are currently sparse.[8] Similarly, there is a growing evidence base on the mental and physical health co-benefits of access to greenspace but little is also known about whether provision of greenspace has wider benefits for the climate. One example is an analysis of cities in 31 European countries using a normalised difference vegetation index that estimated that more than 40 000 annual premature deaths could be prevented by meeting the WHO recommendation of access to greenspace, amounting to about 2·3% of natural-cause mortality. However, greenhouse gas emission reductions were not estimated.[59] Actions that are primarily designed to improve equity, education, and human rights can also have additional greenhouse gas mitigation benefits, but the full potential of such actions is yet to be mapped.

Methods

Measuring climate change mitigation action and health

A research framework was developed to support the main programme of work (appendix pp 1–6). This facilitates the classification, mapping, and characterisation of evidence on climate change mitigation, health, and other study outcomes. Initial development of the research framework was based on a review of existing classifications and frameworks for climate change mitigation actions and health outcomes used by institutions involved in designing or influencing climate policy at an international level, including the Intergovernmental Panel on Climate Change (IPCC),[15,60] Drawdown, OECD,[61] and WHO.[62] The framework also draws on specific resources for classification of behavioural actions,[63] ocean-based actions,[64] actions in the health and education sectors,[65] and urban nature-based solutions.[66] It was designed to respond iteratively to findings generated by the research programme, and therefore the final framework classifies evidence on the basis of the major pathways identified, for which there was substantial evidence of health co-benefits from mitigation actions. The research framework was later superseded by the published research protocol for the umbrella review.[17]

We undertook an umbrella review (a review of systematic reviews) of studies in the academic or policy literature that had quantified both changes in greenhouse gas emissions and health outcomes from one or more actions or policies. An umbrella review enables evaluation of the extent and quality of the existing published systematic literature reviews in the field and aims to create a "cross-sectoral synthesis of evidence on the range of actions available and their effectiveness in mitigating climate change and improving human health".[17] By focusing on systematic reviews, the aim was to identify the most robust previous evidence across sectors and to compare the magnitude of modelled and measured effects of mitigation actions on greenhouse gas emissions and health outcomes. The umbrella review includes both modelled projections and implemented climate change mitigation actions across a range of sectors.

A search for relevant reviews was conducted across multiple peer-reviewed and grey literature databases (the details of the search strategy can be found in the published protocol),[17] identifying 6902 records, of which 317 full texts were screened and 26 systematic reviews were found that met the inclusion criteria of presenting quantitative estimates of both changes in greenhouse gas

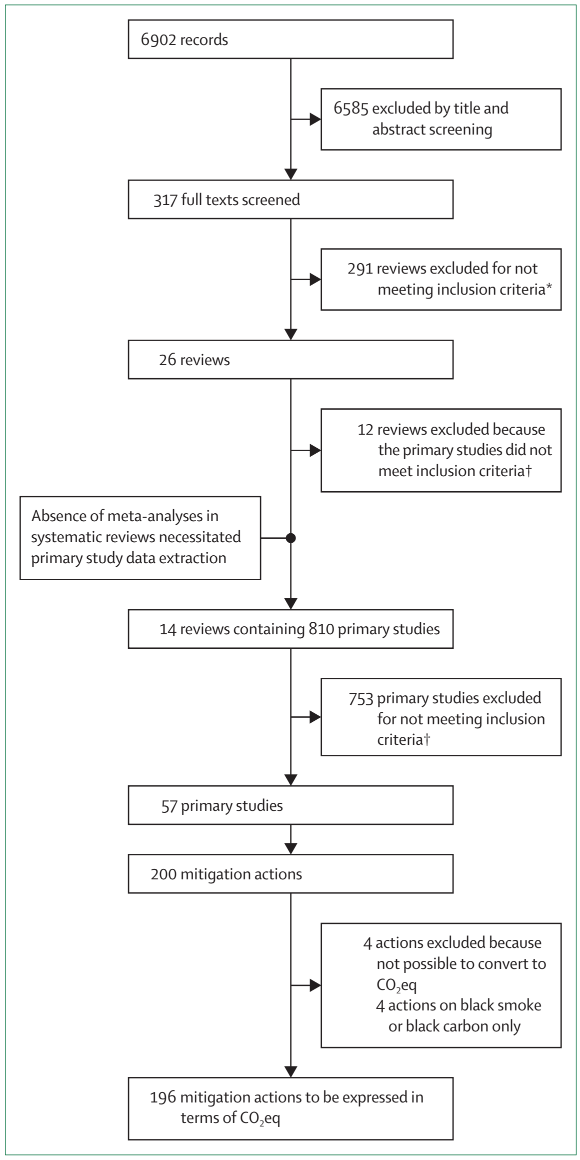

Figure 2: **Flow diagram of search strategy from the umbrella review**
CO_2eq=CO_2 equivalent.*Excluded due to an absence of quantitative estimates of both changes in greenhouse gas emissions and health outcomes. †Excluded due to insufficient context to enable scale-up, absence of baseline measures, and health measures that could not be converted to years of life lost, among other reasons.

For more on **Drawdown** see https://drawdown.org/solutions/table-of-solutions

For **actions in the education sectors** see https://en.unesco.org/themes/addressing-climate-change/climate-change-education-and-awareness emissions and health-related exposures or outcomes (figure 2). Of the 26 reviews included from the search, 11 had conducted a formal meta-analysis and these were all in the Agriculture, Forestry, and Other Land Use (AFOLU) sector. The remaining 15 reviews produced only a narrative synthesis of the included papers.

Due to the absence of meta-analyses in systematic reviews beyond the AFOLU sector, and to obtain comparable quantitative estimates, we extracted data from the primary studies included in each review (including those that had conducted a meta-analysis) for which the primary studies met our inclusion criteria of reporting quantitative measures of both reductions in greenhouse gas emissions and health exposures, risk factors, or outcomes. Some reviews did not contain any primary studies relevant to our analysis (eg, no quantitative estimates were reported) and were therefore excluded from the second stage of our review process (figure 2).

To move from research to implementation, it is imperative to understand the implementation process, including the contextual factors that influence the choice of actions to implement and the impacts these actions might have, both positive and negative, planned and unplanned, on human health or exposures and risk factors for health. We did a separate search of peer-reviewed and grey literature to identify further examples of implemented actions that had measured and reported both emission reductions and health impacts (appendix pp 7–9).[18] These examples provide evidence on the realities of implementing mitigation actions in different geographical locations and socioeconomic settings, and at a variety of spatial scales. The search included a review of relevant articles from the Pathfinder umbrella review and from a systematic mapping exercise, which used machine learning to classify peer-reviewed research papers on climate and health.[67] In addition, pre-existing databases from C40 Cities and CDP were screened, alongside studies submitted in response to a call for evidence published in *The Lancet*.[16] Further targeted searches were carried out for actions with a focus on the enhancement of natural or modified ecosystems to deliver biodiversity benefits while simultaneously addressing societal challenges (ie, nature-based solutions).[68] A list of all evaluated actions submitted through the call for evidence is given in the appendix (pp 7–9).

The actions identified from primary studies eligible for inclusion in the umbrella review were modelled or implemented across a range of spatial, temporal, and measurement scales. Therefore, we undertook a harmonisation process to increase comparability between studies (table). Studied actions were scaled up to 100 000 of the national population. When primary studies included in reviews had undertaken their own estimates of scale-up (eg, city-level scale-up of a localised intervention or national-level scale-up of a city-level intervention), these were used. When no estimates were available from the study itself, spatial scale-up was performed according to the best estimates available in each case; for example, farm-level studies were scaled up on the basis of the number of farms of the same type in the country (appendix pp 10–11), whereas city-level studies were scaled up on the basis of the urban population of the country (ie, it was assumed that the intervention itself could only be carried out in urban populations).

Measures of mitigation and co-impact intensities

Comparable estimates of changes in kilotonnes of greenhouse gases per 100 000 population per year in CO_2 equivalents (CO_2eq) for separate gases, and changes in years of life lost (YLL) per 100 000 population per year were calculated from the quantitative estimates of greenhouse gases and health outcomes (or exposures and risk factors) and according to temporal and spatial scales and units of measurement.

These measures represent carbon mitigation intensity (kilotonnes of CO_2eq per 100 000 population per year) and health co-impact intensity (YLL per 100 000 population per year), which have been used throughout as measures of greenhouse gas reduction and health outcomes, and can be used to compare results of highly heterogeneous studies (appendix pp 10–11). We made several

	Spatial	Temporal	Measurement
Range of scales	Local, farm-level, city-level, national, regional, and global	From 1 week to 50 years	GHGs: relative and absolute changes (ie, percent change and change in tonnes); health outcomes: relative or absolute deaths (ie, percent change or change in number of deaths), DALYs, or YLL
Scale used for harmonisation	National per 100 000 population	1 year	GHGs: kilotonnes of CO_2eq reduced per 100 000 population per year; health outcomes: reduction in YLL per 100 000 population per year
Key assumptions	Population data for the closest year to the year of action were used; urban actions were scaled to the urban population of the country	Effects of actions assumed to be linear over time and per-year effects were used	GHGs and health outcomes in percentages were converted to absolute changes from a baseline scenario, by obtaining baseline sector-specific estimates from national GHG inventories if they were not available from the primary study; deaths and DALYs were converted to YLL using GBD estimates for the same country and year, and the same disease risk or cause of death[69]

CO_2eq=CO_2 equivalent. DALY=disability-adjusted life-year. GBD=Global Burden of Diseases, Risk Factors, and Injuries Study. GHG=greenhouse gas. YLL=years of life lost.

Table: **Data harmonisation process for umbrella review estimates**

For **GBD data** see https://vizhub.healthdata.org/gbd-results/

assumptions in the process of data harmonisation (table); therefore, our comparisons should be regarded as approximate given the limitations of the data available. However, we believe these intensity measures are useful as they allow decision makers to assess the contextually appropriate measures within and across sectors that might have the greatest greenhouse gas impacts and health co-benefits. All greenhouse gas reduction measures are standardised to metric units and given in tonnes, kilotonnes (1000 tonnes), and megatonnes. Implemented case studies are reported in their original units.

CO_2eq emissions in this report are aggregated using global warming potentials over a 100-year time horizon.[5] For CO_2, CH_4, and nitrous oxide (N_2O), these were 1, 28, and 265, respectively, as per the recommendations in the fifth assessment report from the IPCC. Some health exposures (eg, diets) were presented per day but all measured health impacts were based on at least 1 week of data collection.

Some studies only had health exposures available, rather than outcomes, which required modelling to mortality. For air pollution, changes in pollutants were either given in terms of concentrations or absolute weights, and data had initially been extracted for NO_2, nitric oxide (NO), nitrogen oxides (NOx), PM_{10}, and $PM_{2·5}$. In addition, levels of nitrate (NO_3) leaching into soil was extracted for agricultural studies. For health exposures, we used the AirQ+ tool developed for WHO Europe.[70] The tool allowed long-term health effects of $PM_{2·5}$, PM_{10}, and NO_2 to be estimated using a life-table approach, requiring the area under study and all-cause mortality in adults older than 30 years to be entered into the tool (estimated by GBD). Estimated mortality attributable to the pollutant was then converted to YLL. For NOx and $PM_{2·5}$ reported in change in kg, we used an adapted version of the CaRBonH tool also developed for WHO Europe.[70] This tool (which was published in July, 2023, as the CLIMAQ-H tool) can convert emissions of NOx and $PM_{2·5}$ directly to deaths and YLL by estimating changes in exposure, not only in the emitting country, but also in neighbouring countries in Europe. We used the beta version of the tool for this analysis and included health outcomes for the USA and China as well as European countries. Around 156 actions (mostly agricultural studies) that were initially extracted were removed from the analysis at this stage due to the available tools not being able to model the effects of changes in NO and NO_3.

The construction of the harmonised carbon mitigation intensities and health co-impact intensities also enabled us to calculate ratios of health co-impacts to mitigation potential for each action—ie, the number of years of life gained (reduction of YLL) per tonne of greenhouse gas emissions avoided (appendix p 11). However, we did not use these ratios in our results, as they would have given the greatest weighting to actions for which there were large health benefits but small mitigation benefits. For example, the provision of clean cookstoves tends to have large health benefits but modest reductions in greenhouse gas emissions, and so the ratio of health benefits to greenhouse gas benefits would be high. By contrast, actions to change diets can have large benefits for both health and emissions reduction, and using a ratio would make the benefits of these actions appear smaller.

Results

14 systematic reviews were included in our umbrella review following a process of screening all primary studies, and 57 (7%) of a potential 810 primary studies met the inclusion criteria. These 57 studies described 200 individual mitigation actions at the second stage of the review (figure 2), of which 196 could be expressed in terms of greenhouse gas emissions reductions (the remaining four actions focused on black carbon or black smoke). Results are reported at the level of the individual mitigation action rather than the study because many studies included multiple actions. Data from the umbrella review were based primarily on modelled evidence: 178 (89%) of 200 identified actions present modelled results.

Despite extensive searching, few case studies were identified that met the criteria in our search for implemented mitigation actions with measured health co-benefits. Examples of exemplary stakeholder engagement and inclusion were identified, as were actions with potential for significant wins for the climate and environment if taken up at scale. Selected examples are presented here for interventions that exemplify actions to reduce greenhouse gas emissions at the national, city or rural district, and local scale across a variety of sectors, types of intervention, and co-benefit pathways. A full list of identified evaluated interventions is provided online in the Pathfinder Climate Health Evidence Bank.

For the **Pathfinder Climate Health Evidence Bank** see www.climatehealthevidence.org

Sectors and mitigation actions

Most of the evidence in the umbrella review about the effects of specific actions was from the AFOLU sector: 103 (52%) of 200 unique mitigation actions, almost all of which focused on dietary changes (figure 3). The next largest sector was transport with 43 actions (22%), followed by multisectoral interventions (ie, interventions acting across multiple sectors, which are often composed of multiple actions whose impacts cannot be distinguished from one another) with 31 actions (16%). Fewer than ten actions were reported from each of the sectors of buildings (n=9), electricity generation (n=9), and industry (n=6). Most of the actions were conducted at the national level (110 actions [55%]), but there were also 56 actions (28%) at the city level, the effects of which were scaled up to the national level as part of our harmonisation process.

Actions primarily came from high-income settings (129 actions [65%]), with a further 30 (15%) from upper-middle-income settings. All studies from low-income

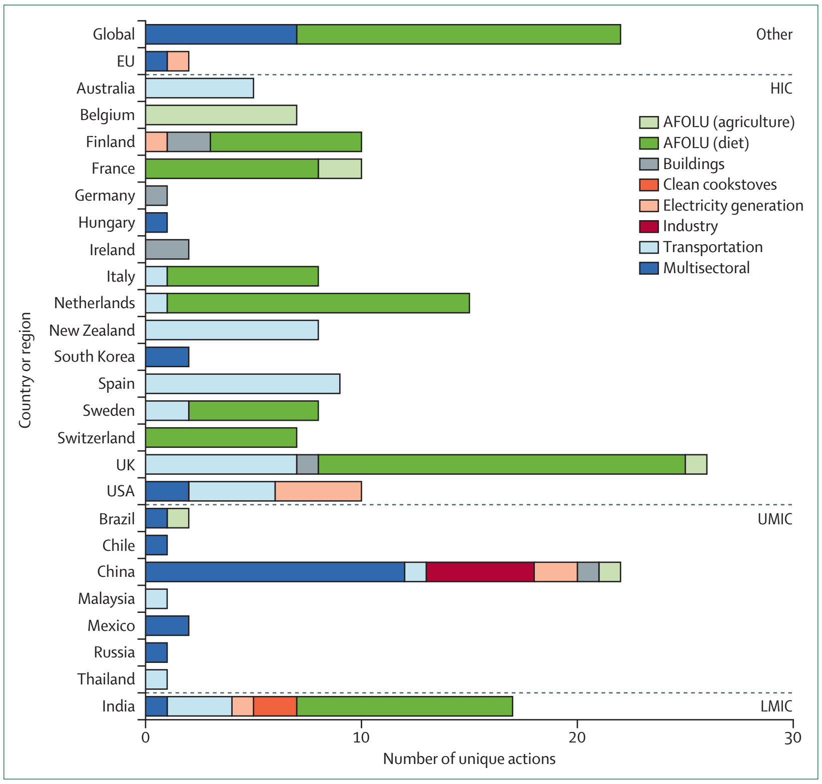

Figure 3: **Unique mitigation actions studied in each country by sector**
These actions include those reducing black smoke and black carbon. AFOLU=Agriculture, Forestry, and Other Land Use. HIC=high-income country. LMIC=lower-middle-income country. UMIC=upper-middle-income country.

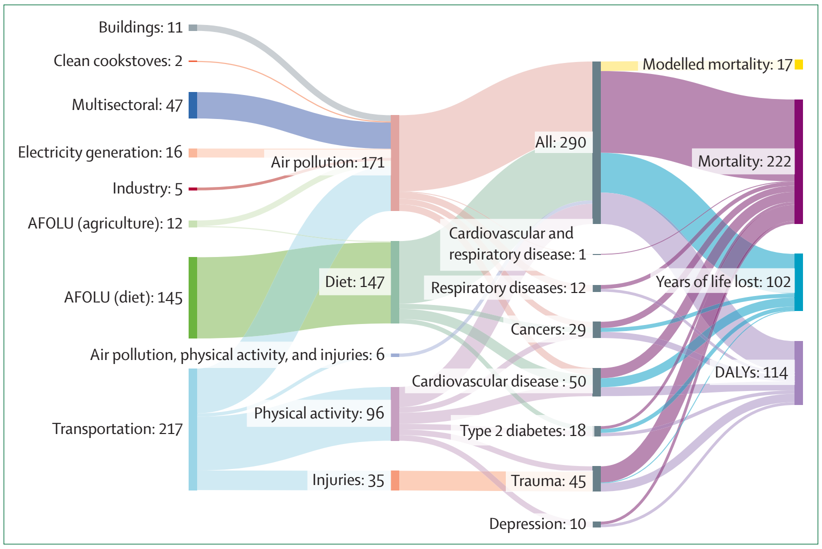

Figure 4: **Mitigation actions across sectors and their associated pathways to health outcomes**
The figure shows all pathways (centre) from actions (left) to health outcomes (right). The action category comprising air pollution, physical activity, and injuries is presented as any combination of the three pathways. 17 pathways to health required modelling from NOx and $PM_{2.5}$ to mortality, as described above, as final health outcomes were not given in the study. Note that these pathways include those from actions reducing black smoke and black carbon. AFOLU=Agriculture, Forestry, and Other Land Use. DALY=disability-adjusted life-years. NOx=nitrogen oxides. $PM_{2.5}$=particulate matter with a diameter of <2·5 μm.

settings were excluded at the second stage of the review because they did not meet the inclusion criteria; India was the only country from a lower-middle-income setting that was included, accounting for 17 actions (19%; appendix pp 12–13). The most common countries included the UK (26 actions [13%], primarily diet interventions) and China (22 actions [11%], mostly multisectoral interventions). Other countries with at least ten actions included Finland (n=10), France (n=10), India (n=17), the Netherlands (n=15), and the USA (n=10), and there were 22 global actions considered (figure 3; appendix p 13).

Measuring health pathways

Within the included studies, four pathways to health were identified: air pollution, diet, physical activity, and injuries (figure 4). Health outcomes themselves were mostly measured in terms of all-cause mortality (primarily from air pollution and dietary risk factors, followed by physical activity and injuries) but there were also some actions in which specific health outcomes, such as cardiovascular disease, cancer, diabetes, and trauma, were estimated. Many actions provided multiple pathways to health (eg, shifting from cars to active transport might affect health via changes in air pollution, physical activity, and traffic injuries, leading to changes in multiple causes of death or morbidity); as such, figure 4 contains more quantified estimates (n=455) than there are unique actions. Estimates were harmonised to the national scale and presented as YLL per 100 000 population per year (table).

The transport sector had the largest number of actions with quantified estimates of the relationship between mitigation action and health (n=217), with pathways to health that were spread across air pollution, physical activity, and injuries (figure 4). The pathway via injuries includes estimates of increased injuries incurred by switching to active travel (particularly cycling) as well as some estimates of reduced injuries from car use. Therefore, this pathway represents a health trade-off as well as a co-benefit. Most studies produced health outcome estimates in the form of mortality rates or numbers of deaths, but a significant number also calculated YLL or disability-adjusted life-years (DALYs). As a comparator, our findings are presented with reference to the GBD estimates for the pathways to health that were most predominant in our findings (appendix p 13).

Measures of greenhouse gases

The most frequently measured greenhouse gas was CO_2 (measured for 101 actions), followed by CH_4 (18 actions), and N_2O (11 actions), with only nine actions measuring black carbon and three actions measuring black smoke (note that some actions measured multiple gases and particles). The remaining 80 actions were measured in terms of the composite unit CO_2eq. CO_2 was measured in all sectors, whereas N_2O and CO_2eq were primarily measured in AFOLU, and CH_4 was mostly measured for multisectoral actions. Black carbon and CH_4 are classified as short-lived climate pollutants (or forcers) because their residence times in the atmosphere are much shorter than CO_2. Black carbon was measured for a group of multisectoral air-quality policy actions and a transportation action retrofitting a local railyard, whereas black smoke was measured in a transportation action to reduce speed limits and for banning residential coal burning in the building sector. However, a definitive method of comparing black carbon and black smoke with CO_2 was not possible. The average residence time of black carbon in the atmosphere is only about 5 days, with substantial regional differences preventing direct comparison with greenhouse gases.[71] Therefore, black carbon and black smoke were not included from this point on—ie, the main body of analysis—although they have considerable effects on health. Estimates of greenhouse gases were harmonised to the national scale and presented as CO_2eq per 100 000 population per year (table).

The challenge of measuring and reporting on greenhouse gases

The CO_2eq of a gas is derived by multiplying the tonnes of the gas by its associated global warming potential, usually over 100 years. Therefore, CO_2eq includes CO_2 as well as other greenhouse gases. Although this is useful because it includes avoided emissions from all greenhouse gases and allows comparisons across different types of actions, it obscures knowledge of which greenhouse gases were affected by a given action and means combining greenhouse gases with quite different residence times in the atmosphere. Actions involving energy and electricity were primarily measured in terms of CO_2 (40 [77%] of 52 actions). Therefore, it is likely that, without any measures of CH_4—which, per unit of mass, has a heating effect 84 times stronger than CO_2 over 20 years (over a 100-year period, CH_4 is 28 times stronger)—the environmental effects of these actions are underestimated. CO_2eq emissions in this report are, if not stated otherwise, aggregated using global warming potentials over a 100-year time horizon.[5] Although CH_4 and N_2O are major greenhouse gases, the focus in the implementation studies was on estimating reductions in CO_2 only, with only one reporting change in CH_4. This contrasts with the umbrella review, in which estimates of other greenhouse gases were found. Future studies should aim to capture information about all greenhouse gases (including short-lived climate pollutants, such as black carbon) affected by a given mitigation action, together with changes in cooling aerosols (eg, sulphates) that might offset some of the climate benefits.

Mitigation and health co-impacts

The greatest average mitigation intensities were seen for electricity generation, followed by multisectoral actions (figures 5, 6). All these actions with a high impact on greenhouse gases affected health via reduced exposure to air pollution (figure 4). The remaining sectors had an average mitigation intensity around a quarter or less of that of electricity generation. Actions to improve cookstoves had the highest median health co-impact intensity with a reduction of 1279 YLL per 100 000 population per year, followed by actions to change diets with a median intensity reduction of 306 YLL per 100 000 population per year. However, the greenhouse gas benefits from improved cookstoves are small relative to those from changing diets and much smaller than replacing fossil fuels with clean renewable energy for electricity generation. Actions in the buildings, transportation, industry, and agriculture sectors tended to have smaller effects on both greenhouse gases and health per 100 000 population than actions towards dietary change. The overall impact of any action will be dictated by the total potential scale of uptake (eg, the scope for implementation of clean cookstoves is much smaller than the scope for replacement of fossil fuels with

For more on **short-lived climate pollutants** see https://www.ccacoalition.org/en/content/short-lived-climate-pollutants-slcps

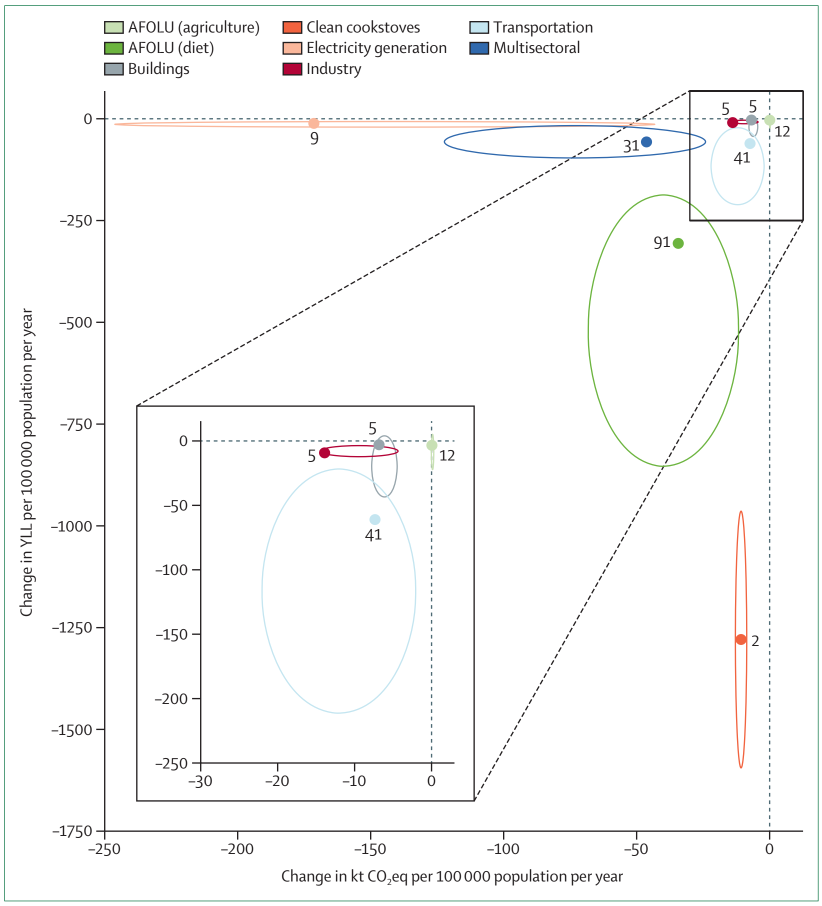

Figure 5: **Climate and human health impacts of mitigation action by sector**
Ellipse height corresponds to the IQR for each sector's change in health co-impact intensity (YLL per 100 000 population per year) and ellipse width corresponds to the IQR for each sector's change in carbon mitigation intensity (kt CO_2eq per 100 000 population per year), whereas the plotted points are the median and the numbers indicate the number of actions. Some estimates of environmental impact could not be converted to CO_2eq (eg, black carbon and black smoke); hence, there were fewer actions for the buildings and transportation sectors than for other sectors. AFOLU=Agriculture, Forestry, and Other Land Use. CO_2eq=CO_2 equivalent. kt=kilotonnes. YLL=years of life lost.

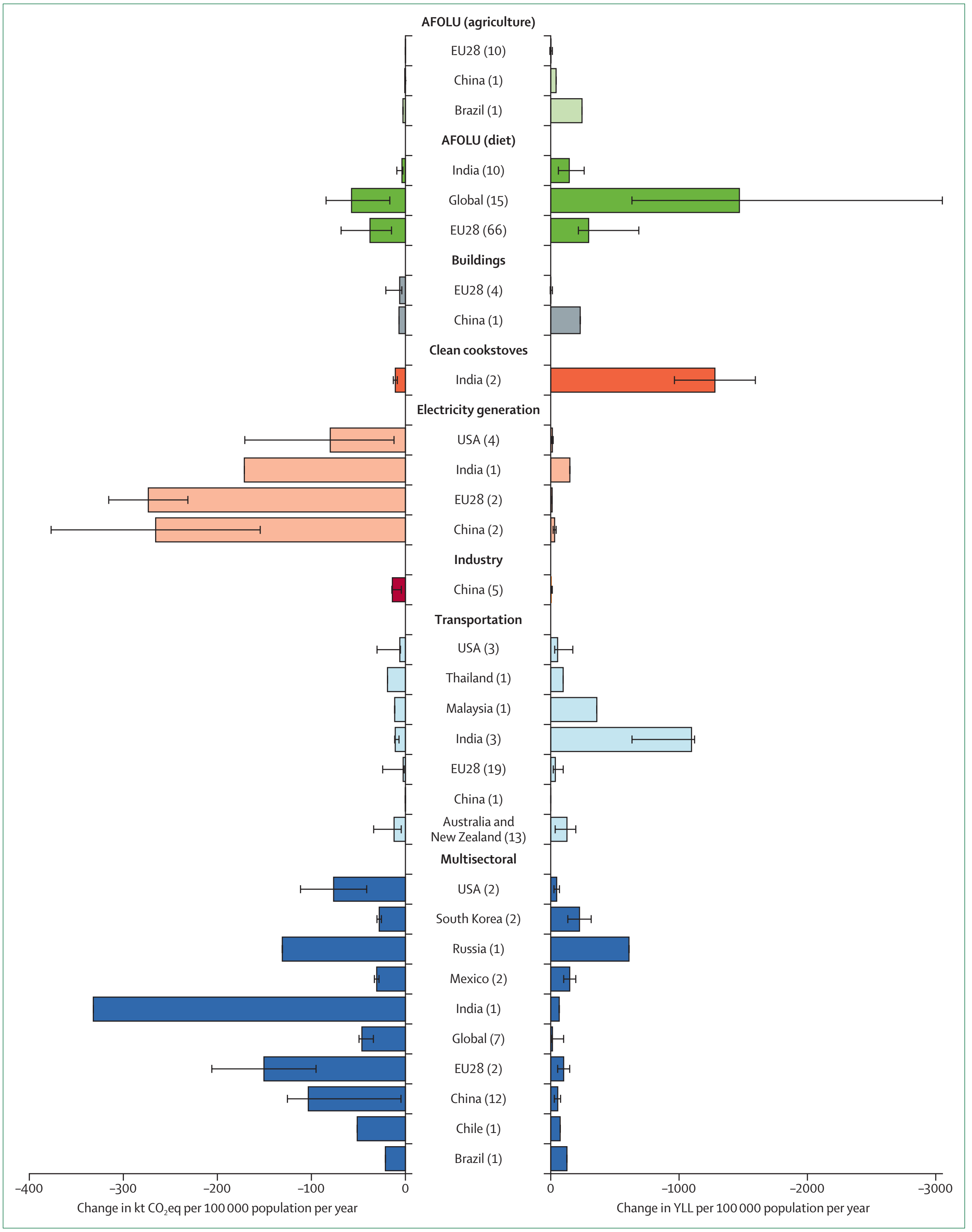

Figure 6: **Variation in carbon mitigation intensity across sectors**
This figure presents the median change in kt CO_2eq/100 000 per year and the change in YLL per 100 000 population per year, compared with business as usual and split by country context. The black bars represent the IQR for estimates. The number of actions is given in parentheses. AFOLU=Agriculture, Forestry, and Other Land Use. CO_2eq=CO_2 equivalent. EU28=all 27 countries of the EU plus the UK. kt=kilotonnes. YLL=years of life lost.

renewables for energy generation, with the latter reducing ambient air pollution exposure for much of the world population).

We identified some major differences in intensities between studies from different countries. For example, the health co-impact intensities of transportation actions were larger in India than in other countries, due to higher baseline levels of air pollution (figure 6). There are also likely to be differences between studies within the same country due to factors such as whether local energy generation systems are coal-based or more reliant on gas or renewables. Study design is likely to have played a part in some of these differences, with some bias towards large modelling studies likely to overstate potential impacts, particularly among the diet studies. Variation in health co-impact intensities from similar actions tended to be larger than variation in mitigation intensities, which probably reflects different approaches to modelling health effects.

Energy

The energy sector contributes the largest proportion (33%) of global greenhouse gas emissions[15] and therefore actions to mitigate these emissions will be central in finding pathways to net zero. There are also substantial potential health benefits, largely from reduced air pollution, depending on location. Phasing out coal combustion will yield the largest health and climate benefits,[72] being responsible for about 50% or more of fossil fuel-related air pollution on a global scale, with widely differing contributions by country depending on the energy mix and the emission standards of power stations (see Energy case study).[39] Gas combustion produces negligible quantities of sulphur dioxide, mercury, and particulates, and is therefore less polluting than coal but is responsible for substantial greenhouse gas emissions, both from gas leaks that emit CH_4 (thus contributing to tropospheric O_3) and from CO_2 when burnt. The effects of NO_2 exposure from household gas combustion on the risk of asthma and of ambient NO_2 from various sources on the incidence of asthma in children and adolescents are discussed in the Buildings results section.[73,74]

In 2022, the stock of renewable energy capacity increased by an unprecedented 9·6% and amounted to almost 295 gigawatts of energy from renewables. Renewables accounted for 40% of installed power capacity globally by the end of 2022, with solar power accounting for two-thirds of the increase in renewables.[75] However, many energy challenges remain to achieving scale-up, including grid flexibility to support integration of variable renewable power. To limit global temperature increases to 1·5°C above pre-industrial levels, the world needs more than 1000 gigawatts of renewable capacity additions every year until 2050, with solar power contributing more than 50% of the new renewable capacity. Of particular concern, global coal use is estimated to have risen by 1·2% in 2022, exceeding 8 billion tonnes in a single year for the first time, according to the International Energy Agency.[76] On the basis of current market trends, coal consumption is forecast to plateau at that level by 2025, driven by growing demand in emerging Asian economies. As a result, coal will continue to be easily the largest single source of CO_2 emissions from the global energy system. Thus, much greater ambition is needed to bring emissions reductions on track to reach net zero by 2050 or earlier.

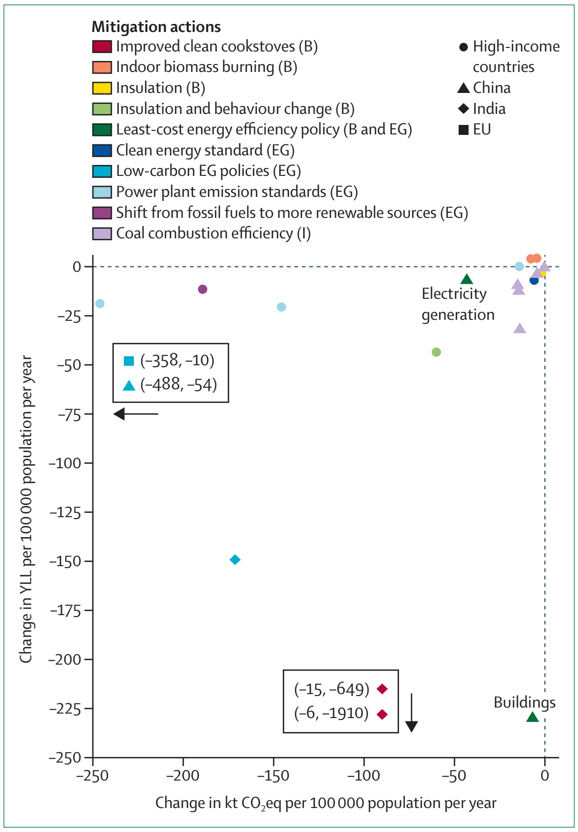

Figure 7: **Climate and human health impacts of mitigation actions in the electricity generation, buildings, and industry sectors**
The electricity generation, buildings, and industry sectors were grouped in one graph as they all involve changing energy use. The different-shaped points represent different types of country. Note differences in the vertical scale for changes in YLL when making comparisons between sectors. B=buildings sector. CO_2eq=CO_2 equivalent. EG=electricity generation sector. I=industry sector. kt=kilotonnes. YLL=years of life lost.

Electricity generation

Evidence from the umbrella review showed that actions in the electricity generation sector gave both the largest median mitigation intensities and the largest variability between action types, with actions such as decarbonising power generation having large benefits, whereas urban policy and energy efficiency actions tended to have much smaller effects (figures 6, 7). The health co-benefits from reduced ambient air pollution (including those in the electricity generation sector) appear small compared with the co-benefits predicted from dietary change but a wide range of estimated deaths from ambient $PM_{2.5}$ air pollution attributed to fossil fuels are observed within the studies reviewed. This discrepancy is likely to reflect the relatively low level of ambition for some of the actions and the relatively low baseline levels of air pollution in many of the countries studied. Co-impact intensities were higher for studies from India and China than for studies from other countries.[77] One study considering low-carbon electricity generation action in three different locations (the EU, China, and India) generated varying health co-impact intensities depending on the baseline level of air pollution; the EU had both the lowest baseline air pollution levels and the smallest health benefits (showing reductions of 10 YLL per 100 000 population per year), followed by China (54 YLL per 100 000 population per year) and then India (149 YLL per 100 000 population per year).[78]

Variation in estimates is also dependent on the exposure–response function (ERF) used, the health outcomes included, the counterfactual used for comparison (for non-linear functions), the magnitude of the mitigation action, and other factors.[77] The range of estimates will probably converge in coming years as further advances in knowledge lead to the attribution of additional health outcomes to air pollution and reduce uncertainties in the ERF.[77]

Some studies and implemented actions might underestimate the health co-benefits due to methodological limitations.[43] The transboundary nature of air pollution means it is important to consider the positive spillover effects of national air pollution. Such reductions are increasingly being modelled and included in estimates[70,79] but might be absent in older studies.

Within the umbrella review, actions affecting health via ambient air pollution used a wide range of ERFs to estimate health impacts. This heterogeneity was often compounded by opaque methods that did not detail the exact functions used, making quantitative inferences regarding the impact different ERFs had on effect sizes difficult. However, some studies did specify their ERFs, allowing us to further understand the observed health co-benefits (appendix p 14).

For the **WHO air pollution guidelines** see https://apps.who.int/iris/handle/10665/345329

Recent evidence of the adverse effects of low levels of air pollution has resulted in more stringent WHO ambient air pollution guidelines and implies that the health benefits of reducing air pollution are greater than those estimated in many studies. Additionally, there were fairly few studies from areas with high air pollution levels.

Developing and delivering sustainable energy might disproportionately affect Indigenous communities, ethnic minorities, and low-income communities.[80] For example, many dryland areas used by pastoralists provide excellent conditions for solar and wind power plants, as they are often sparsely populated and are exposed to high solar radiation.[81] However, pastoralists are often not adequately informed of their rights or consulted about the energy projects. Therefore, green energy projects can interfere with livestock migration routes and access to pasture, and disrupt the pastoral land-use system. As a result, local communities might be forced to migrate to different areas, often with less favourable conditions, making it harder to maintain their traditional farming systems and creating food and financial insecurity.[82] Increasing active participation by all communities affected by new developments can help to identify potential trade-offs, with a view to maximising synergies and minimising negative impacts. Where trade-offs exist, action can be taken to reach compromise across all affected groups, and possibly to facilitate compensation for economic losses incurred.

Energy case study: CO_2 emission reduction from electricity generation and improved air quality in the USA

Several changes took place in the power sector in the USA during the 2005–16 period,[83–85] including decommissioning of coal-fired power plants and an increase in solar and wind power replacing both coal and natural gas in electricity generation. The percentage of renewable energy that replaced fossil fuel generation varied widely between regions in the USA over the period in question. This was partly due to varying levels of stringency between states in meeting particular policies, such as the renewable portfolio standards, which require electricity companies to meet a growing portion of their load with eligible forms of renewable electricity.

In total, 147 megatonnes of CO_2 emissions were avoided from wind and solar power generation in 2015 alone, and over the whole study period improvements in air quality were estimated to have avoided between around 3000 and around 13 000 premature deaths. In addition, meeting compliance obligations for renewable portfolio standards in 2013 also resulted in a reduction in power-sector water withdrawals and consumption, equivalent to about 38 000 L of withdrawal and 1200 L of consumption saved per megawatt-hour of generation of renewable electricity. The economic benefits of renewable energy power generation were estimated at between US$30 billion and more than $100 billion.[83,85]

In a separate complementary action in the USA, 334 coal-fired power units at 138 facilities were closed and 612 new natural gas-fired units across 243 facilities were brought online between 2005 and 2016. This led to an estimated 22 563 (95% CI 16 896–43 428) fewer premature deaths from air pollution-related conditions and, as a beneficial effect of reduced aerosol and O_3 levels, crop yields increased by an estimated 329 million (95% CI 169–490) bushels of corn over this period.[84] However, the use of natural gas as a transition fuel from coal to renewable energy should be treated with caution in view of the accompanying (albeit lower) CO_2 and CH_4 emissions, as well as other negative consequences of fracking.[86]

In 2021, about 61% of electricity generation in the USA was from fossil fuels, 19% from nuclear energy, and 20% from renewable energy sources. Therefore, there is major scope to scale up these actions with additional benefits for health and greenhouse gas emissions. For example, it was estimated that nearly 52 000 lives could be saved annually by transitioning from coal to photovoltaic-powered electrical generation, which requires 755 gigawatts of US photovoltaic installations.[87] Rigorous procedures to ensure accountability and compliance can help to promote the achievement of policies and regulation standards designed to reduce greenhouse gas emissions. In addition, current utility rate structures hinder the deployment of renewable energy and a change to distributed generation in the system would be required. Standard procedures to connect renewable energy systems to the electrical grid are lacking and policies to address the sparse access to renewable energy sources in remote areas are required, including potential use of biogas, solar mini-grids, and mini-hydro facilities.

Industry

The energy requirements of the industrial sector primarily affect human health through exposure to air pollution from manufacturing and processing, although industrial accidents and pollution are also a notable cause of morbidity and mortality in many countries.[39] Our review found sparse evidence from the industrial sector, and all the included studies were based on small-scale strategies to reduce pollution from coal in China with no studies on industrial processes that did not involve fuel burning, such as those involved in cement or steel manufacture. Consequently, the mitigation and health co-impact intensities were fairly small (figure 7). These were also city-level actions and therefore largely accrued health benefits for people residing in urban areas (~41% of people in China at the time of the reported study, currently ~65%). Many of the interventions were found to be highly context-specific, requiring evidence from real-world examples of their implementation to accurately assess co-benefits and trade-offs.

The large environmental footprint of the industrial sector has led to increasing calls for implementation of circular economy approaches that reduce waste and the demand for primary materials in manufacturing processes, but we did not find any estimates of the health effects of such a transition. Biomass wood burning has been adopted in several high-income countries in response to climate change policies endorsing the use of renewable energy sources. A range of negative health impacts have been linked with household and ambient air pollution that results from the burning of such biomass. In 2015, more than 40 000 premature deaths per year in Europe were attributable to biomass smoke.[88] A report on the use of woody biomass for energy in the EU pointed to major data gaps that make it difficult to ascertain whether and, if so, how much these actions contribute to climate mitigation in the near term, given the long periods required for the growth of mature trees.[89]

A further example of a trade-off is the need to accompany actions to cut sulphate emissions with cuts in short-lived climate pollutants to offset the increased heating that would otherwise occur, because sulphates are cooling aerosols and have probably contributed to a cooling of between 0·0°C and 0·8°C since the baseline period of 1850–1900.[90,91]

For more on **US energy generation** see https://www.eia.gov/tools/faqs/faq.php?id=427&t=3

Buildings and infrastructure

The housing sector is responsible for substantial greenhouse gas emissions. For example, about 20% of greenhouse gas emissions in the USA result from residential energy use, with marked inequalities in per-capita emissions because of larger residences and the use of more energy-hungry appliances among high-income households than among lower-income households.[92] A combination of decarbonisation of the energy system and deep retrofits of existing housing stock will be needed to reduce greenhouse gas emissions drastically and improve health. Retrofitting existing houses with improved insulation can reduce cold exposure in temperate climates, but such actions need to avoid reducing ventilation and thus increasing household air pollution, including from tobacco smoke and combustion of gas or solid fuels. The combination of insulation with efficient ventilation in the most tightly sealed dwellings can yield substantial benefits for both health and greenhouse gas emissions. No studies examined the potential for mitigation savings and health benefits from actions in waste and sanitation but the potential for action in this area is significant (panel 3).

In low-income countries, there are major potential health benefits from reduced household and ambient air pollution by replacing solid fuels with clean sources of energy. However, a previous systematic review has shown that improved combustion stoves or venting (eg, through flue or chimney) were less effective than cooking with clean fuels, including ethanol, liquefied petroleum gas, and electricity, at lowering $PM_{2·5}$ concentrations. In practice, stove stacking (whereby polluting sources of energy continue to be used alongside clean fuels) and high background concentrations of ambient air pollution have prevented most clean fuel interventions from reaching the WHO interim target $PM_{2·5}$ level 1 of 35 μg/m³. More integrated approaches addressing ambient and household air pollution in tandem are needed.[112] The climate benefits of cleaner household energy in low-income settings are due partly to reduced black carbon emissions[113] and, in some cases, reduced deforestation. In countries such as India, liquefied petroleum gas is used to replace solid fuels in households and, although it is a fossil fuel, there is evidence that there are modest net

Panel 3: Tackling methane emissions while improving sanitation

Actions on sanitation were absent from the umbrella review. Sustainable waste and sanitation actions are closely linked to the circular economy and urbanisation. Solid waste (ie, refuse generated as a by-product of household, public, and commercial processes) dumpsites are thought to contribute 20% of global methane (CH_4) emissions and 11% of black carbon due to anaerobic decomposition and burning.[93] There is good evidence for health benefits arising from the adoption of household sanitation, including on-site waste disposal (eg, pit latrines) and off-site disposal (transport and storage through sewerage systems) or container-based approaches (appendix p 26).[94] Analyses of multiple large-scale trials, observational studies, and natural experiments suggest 30% reductions in reported diarrhoea from well designed sanitation actions.[95,96] Sanitation promotion with a community-level component is able to significantly reduce rates of open defecation by encouraging access to, and use of, latrines at the household level (household or unshared sanitation),[97] leading to 50% fewer diarrhoea deaths in childhood.[98] Other benefits from improved sanitation have been reported, especially for women and girls, including safety and psychosocial health,[99] improved menstrual hygiene reducing urinary tract infections,[100] and improved school attendance.[101]

The choice of technology might have important implications for greenhouse gas emissions. Accessible on-site sanitation in rural areas is often provided in the form of pit latrines; however, there can be problems in maintaining them for healthy and comfortable use and ensuring they are regularly emptied. Therefore, the installation of double-pit latrines is a preferred option as they do not need to be emptied as frequently and the faecal waste decomposes into reusable soil.[102] However, concerns have been raised about the potential emissions arising from standard pit latrines, which use anaerobic decomposition releasing CH_4, a major source of greenhouse gas emissions estimated to comprise around 7% of emissions in India.[102,103] One solution is to increase coverage of sewerage systems, which is a priority in many urban areas and known to be beneficial for health[104] but is limited by infrastructure costs of household sewer connections. Other solutions include composting, which uses aerobic decomposition,[105] and container-based sanitation, where container pits are transported off site for central processing,[106] but this is costly to scale up and requires road access.[107] CH_4 production can be reduced through source separation of urine and faeces, such as dry desiccating toilets (composting latrines with urine diversion).[105] Digestors (eg, bacteria or macro-organisms) have also been developed to prolong the lifetime of pit latrines, enhancing their use with CH_4 produced as a by-product.[108] The CH_4 produced by these approaches can also be captured and stored as biogas, for use as a clean fuel.[102] Large-scale increases in pit latrines pose important challenges for combating global CH_4 emissions. The development and laboratory testing of suitable technologies, and their evaluation for greenhouse gas and health benefits at scale in field trial settings, is under-researched.

Depending on the type of solid waste and context, sanitary management might comprise recycling, composting, landfill, compaction, or incineration. For example, organised waste collection and processing can improve household waste management and reduce exposure to disease-carrying pests.[109] Non-organic material must be separated from compostable organic material, which can be disposed of through sanitary landfill, providing income and employment from recycling for those living in the vicinity of the dumps. Systematic evidence suggests that effective strategies to reduce CH_4 emissions from organic materials include the addition of bulking agents and turned composting, which allow aerobic decomposition, potentially reducing CH_4 emissions by more than 70% each.[110] The value of composting to agriculture is greatest when faecal waste is added to the refuse, as done on a wide scale in India and China. However, because of the complexity of determining the appropriate mix of additives and turning times, effective methods for delivering composting toilets at scale in rural areas remain to be found.[111]

climate benefits.[45] To achieve total rural electrification and universal access to clean-combusting cooking fuels and stoves by 2030, an additional investment of $65–86 billion (reference base price year 2005) per year until 2030 would be needed. Improved access to modern cooking fuels alone can avert between 0·6 and 1·8 million premature deaths annually in 2030.[114]

Clean cookstoves also offer significant opportunities to reduce gender inequality, including by improving women's health and by reducing time poverty. By reducing the time spent on fuel collection, women gain a greater opportunity to undertake extra economic activity or further their education; additionally, exposure to violence during fuel collection might be reduced.[28]

In our review, the greatest health co-impact intensities were seen in clean cookstove studies through reductions in air pollution, which were found to have average reductions in YLL of more than 1279 (ie, 1279 years of life gained) per 100 000 population per year (figures 6, 7). Mitigation intensities for these actions tended to be low but, scaled up to large populations in countries such as India (where all the included studies took place), they could still be substantial. The domestic burning of solid fuels also contributes about 10% of the 3·5 million incident cases of asthma in children and adolescents annually that are attributable to NO_2.[74] Although gas cooking appears less health-damaging than burning solid fuels, a meta-analysis showed that, in children, the risk of asthma is increased by gas cooking and exposure to indoor NO_2 increases the risk of current wheeze.[73] Other actions involving improving energy use in buildings included home retrofitting and behaviour change and showed smaller mitigation intensities than other actions involving energy, but again these could still be substantial at scale (figures 6, 7; see Building Retrofitting case study and further examples in the online Climate and Health Evidence Bank).

Building retrofitting case study: the Victorian Healthy Homes Program

A randomised controlled trial in the state of Victoria, southeast Australia, funded by the Sustainability Fund of the Victorian Government and by Sustainability Victoria, assessed the impact of energy efficiency and thermal comfort upgrades on electricity and gas usage, temperature, health-care utilisation, self-reported health, and quality of life in the state of Victoria. The programme upgraded 984 low-income houses across western Melbourne and the Goulburn Valley between 2018 and 2020. Upgrades included insulation of ceilings and underfloor spaces, draught sealing, space heating, and internal window coverings at an average upgrade cost of AU$2809 per household. Households were divided into intervention (upgraded before winter) and control (upgraded after winter). Indoor temperature was measured every 30 min using a data logger installed in the main living area. A regression model was developed to establish whether households with an upgrade experience higher average home temperatures than households without an upgrade. The surveys included questions on self-reported health conditions (including cardiovascular disease, asthma, and COPD) and breathlessness, thermal comfort, and quality of life.

The outcomes from the control and intervention groups during the 3-month winter period of the study year were compared and showed that the home upgrade on average reduced gas use by 2·326 gigajoules and electricity use by 81·9 kilowatt-hours over the 3-month winter period, which can be converted to a reduction of 0·128 tonnes of CO_2eq per upgrade for gas and 0·078 tonnes of CO_2eq for electricity. Average savings in energy were AU$85 in the intervention group over the winter period. After winter, the intervention group had significantly higher mental health scores than the control group (coefficient 1·73 [95% CI 0·21–3·25]; p=0·026). The analysis showed no significant difference between the groups in asthma control or in COPD symptoms over winter, but the intervention group had a reduction in breathlessness relative to controls over winter. The intervention group also had fewer days absent (mean 5·4) from usual activities than the control group (mean 7·3). Total health-care costs were lower for the intervention group (mean AU$3394) than for the control group (mean AU$4172) and the intervention households were significantly warmer than the control households (by 0·33°C [95% CI 0·05–0·60]; p=0·022).[115]

The Victorian Healthy Homes Program showed how a relatively minor home insulation upgrade can improve health outcomes and reduce emissions. These results are potentially applicable to other countries with inefficient energy housing stock.

Multisectoral actions

Actions that cut across multiple sectors had the second largest average mitigation intensity after electricity generation, and these actions were mostly national policies that included increased energy efficiency across buildings, transport, and industry or packages of measures to improve air quality and reduce CH_4. Health co-impact intensities were mostly moderate, and this is probably because the basket of actions included in each national policy included some policies with large co-benefits (eg, changes to transport) and others with negligible benefits for health (eg, manufacturing efficiency standards; figures 6, 8).

The impacts of multisectoral actions were highly variable depending on the country context; the largest greenhouse gas impacts were seen in a single study considering various mitigation measures involving industrial processes and energy activities, taking place in multiple sectors, in China (–910 kilotonnes CO_2eq per 100 000 population per year), India (–332 kilotonnes CO_2eq per 100 000 population per year), and the EU (–261 kilotonnes

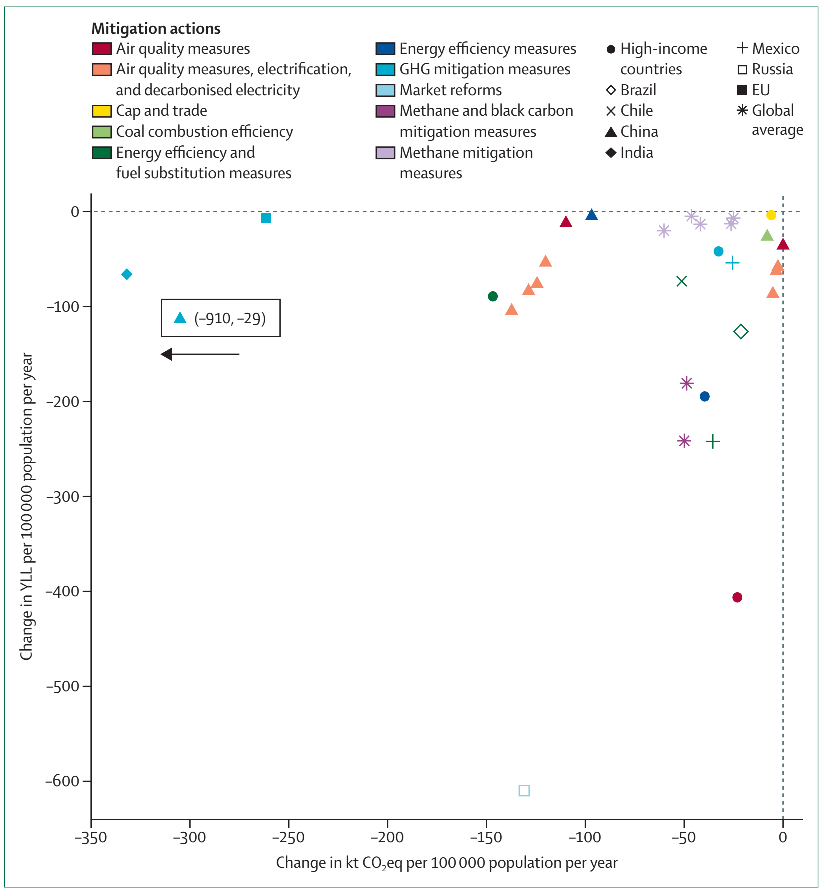

Figure 8: **Climate and human health impacts of mitigation action from multisectoral actions**
The different-shaped points represent different types of country: circles represent high-income countries; open diamonds represent Brazil; crosses represent Chile; triangles represent China; pluses represent Mexico; open squares represent Russia; stars represent global averages; diamonds represent India; and closed squares represent the EU. Note differences in the vertical scale for changes in YLL when making comparisons between sectors. CO_2eq=CO_2 equivalent. GHG=greenhouse gas. kt=kilotonnes. YLL=years of life lost.

CO_2eq per 100 000 population per year; figure 8). As seen in electricity generation with actions impacting health via air pollution, this same study found the greatest reductions in YLL in India (–66 YLL per 100 000 population per year), followed by China (–29 YLL per 100 000 population per year) and the EU (–7 YLL per 100 000 population per year). Large greenhouse gas impacts for multisectoral actions were seen in national mitigation policies in Russia and the USA, with benefits in Latin America being the smallest on average (figure 6). The largest health co-impact intensities were found from national mitigation policies in Russia, where baseline health burdens are high.

Transport

Actions implemented in the transport sector include a range of incentives (eg, free bus passes and bicycle maps), improved infrastructure (eg, bicycle lanes), and sanctions (eg, taxation, congestion charges, restrictions;[116] see transport case studies). These measures can improve air quality, reduce injury and accident rates, and benefit health through increased physical activity (eg, through increased walking and cycling). However, the achievements of major benefits for both the climate and health require systemic changes that combine increased use of public transport and active travel with reduced private car use. Single interventions generally have small effects. The replacement of fossil fuel-powered private cars with electric cars powered by electricity from renewables will reduce greenhouse gas emissions and air pollution from NO_2 and probably also from $PM_{2·5}$, but it does not achieve health benefits from increased physical activity, nor will it reduce road danger for pedestrians and cyclists. The land transport sector contributes about 44% of the approximately 3·5 million incident cases of asthma in children and adolescents worldwide that can be attributed to ambient NO_2 levels.[74] However these potential co-benefits were not quantified in the studies reviewed. In the UK, fine particles from the wear of brakes, tyres, and road surfaces currently constitute 60% of primary $PM_{2·5}$ emissions from road transport and will become more dominant in the future as tailpipe emissions decline.[117] It is currently unclear what effect a switch to electric vehicles will have on this type of pollution—it will depend on vehicle mass, the use of regenerative braking, tyre composition, and driving patterns.[118]

There is also a potential for spillover effects because of the increasing demand for cobalt for use in batteries for electric vehicles. Hazardous artisanal cobalt mining, in which informal miners use bespoke and unsafe methods to extract cobalt (sometimes involving child labour), is common in DR Congo, with around 150 000–200 000 artisanal miners and many more dependent on their income. For this reason, the DR Congo Government set up the Enterprise Générale du Cobalt in 2009 to regulate artisanal mining, giving the miners opportunities to work legally, prevent tension and conflict around the mining sites, and reduce accidents,[119] but results still require independent evaluation.

We found generally modest carbon mitigation intensities in the transport sector, with the largest intensities seen among transportation actions for which the intervention involved reduction in private car use and increased public transport or active travel. The provision of bicycle infrastructure alone had small average mitigation intensity (figures 6, 9). Health co-impact intensities were also modest, but some actions, such as carbon caps in the transportation sector and switching to active transport in India, had large health co-impact intensities (predominantly from increased physical activity but also reduced air pollution). Similar interventions in other contexts had lower health co-impact intensities (eg, where increased cycling did not result in substantially reduced driving and therefore air pollution concentrations remained similar) and some of these included trade-offs for health through increased injuries from walking or cycling.

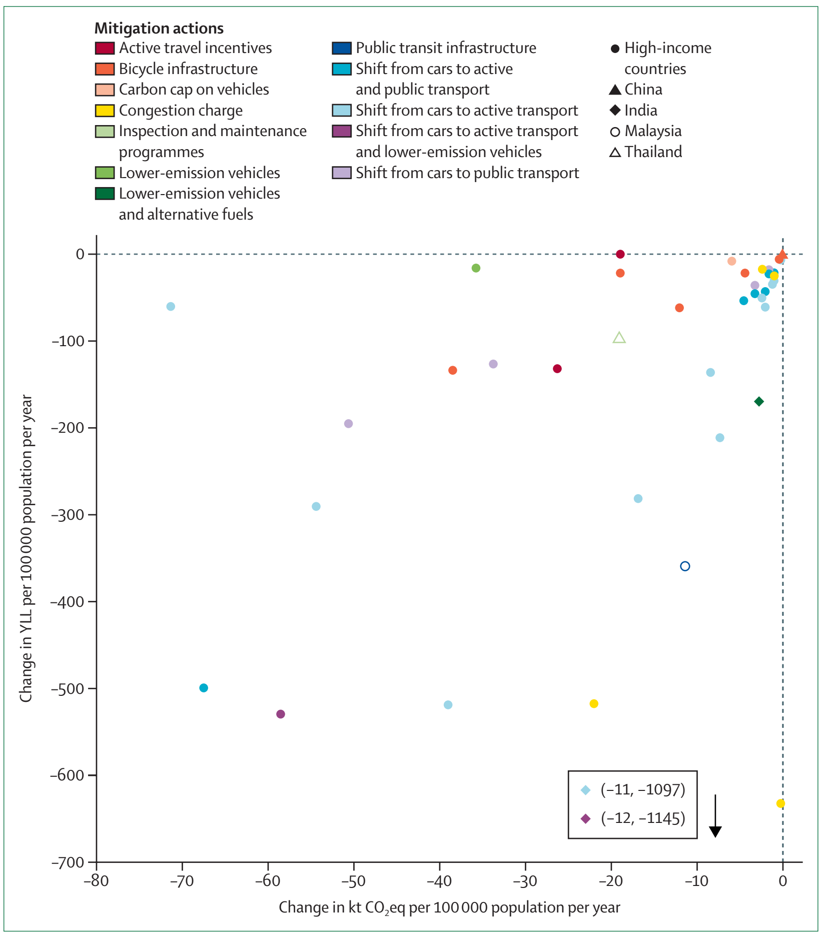

Figure 9: Climate and human health impacts of mitigation action in the transport sector
The different-shaped points represent different types of country: circles represent high-income countries; triangles represent China; open circles represent Malaysia; open triangles represent Thailand; diamonds represent India. Note differences in the vertical scale for changes in YLL when making comparisons between sectors. CO_2eq=CO_2 equivalent. kt=kilotonnes. YLL=years of life lost.

Well designed actions in the transport sector can improve equity at the same time as making travel more sustainable. For example, in 2017, the city of Quito in Ecuador identified that residents believed the local public transportation system to be unsafe. To improve sustainable transport within the city, they developed a campaign to increase the use of public transport, implementing both infrastructure changes and a harassment reduction campaign. Changes included the installation of glass corridors to provide safe waiting areas. Although changes in public transport use and thus greenhouse gas reductions are yet to be quantified, they have so far succeeded in reducing gender-based violence by 34·5% since 2017.[120]

Transport case study: Tokyo Vehicle Emission Reduction Program

The Tokyo Metropolitan Government, Japan, has introduced several measures to tackle environmental issues caused by rapid industrialisation and the mass adoption of cars since the economic boom after World War 2. In the 1970s, the city implemented measures to regulate air pollutants from factories. With an increase in air pollution due to rising traffic volumes at the beginning of the 21st century, the city also introduced a range of regulations for cars, such as the Vehicle Emission Reduction Program. The aim of the initiative is to encourage businesses to implement environmentally friendly actions, such as switching to low-emission and fuel-efficient vehicles. The regulation requires businesses with 30 or more vehicles to submit a 5-year Vehicle Emission Reduction Plan and an annual performance report, outlining their fuel consumption and efforts to reduce greenhouse gas emissions and air pollution. Since 2022, businesses with 200 vehicles or more are legally required to have 30% of their vehicle fleet consisting of low-emission and fuel-efficient vehicles and 20% of their passenger car fleet must be battery electric vehicles, plug-in hybrid electric vehicles, or fuel-cell vehicles.

As part of the Vehicle Emission Reduction Program, each year, the Tokyo Metropolitan Government also selects 120 businesses on the basis of their plans and reports and provides them with advice and guidance on emission reduction actions. More than 1500 businesses submitted their plans and reports in 2021. CO_2 reductions were calculated on the basis of the fuel consumption of each vehicle used by each business, and NOx and PM_{10} reductions were calculated on the basis of vehicle type and mileage of each vehicle, from each business. Between 2016 and 2021, total emissions decreased by 440 000 tonnes of CO_2, 1367 tonnes of NOx, and 49 tonnes of PM_{10} from businesses covered by the Vehicle Emission Reduction Program.

There are currently no plans to scale up the Vehicle Emission Reduction Program. However, moving to low-emission or zero-emission vehicles would significantly decrease the CO_2 emissions of the transport sector in Tokyo. The transport sector alone accounts for around 20% of the city's total CO_2 emissions, of which 78% can be attributed to cars.

Further research into this initiative would provide invaluable information on how to scale up this initiative to other parts of Japan or elsewhere. This includes information on why businesses were motivated to voluntarily implement concrete changes or how they were motivated to do so by the Tokyo Metropolitan Government and which changes were feasible to implement.

Transport case study: active travel in New Plymouth, New Zealand

The Model Communities Programme is a central and local government-funded initiative focusing on the promotion of cycling and walking, as well as infrastructure investment, to improve urban active travel networks in New Plymouth and Hastings in New Zealand. As part of the programme, New Plymouth added 12 km of off-road facilities and 20 km of bicycle lanes, installed bicycle parking, widened path entries, created several shared spaces with reduced speed limits for vehicles (30 km/h), and ran media campaigns, events, and bicycle-skills training. Hastings added 30 km of arterial paths (roads that provide direct routes for long-distance travel throughout the city) and 50 km of on-road and off-road walking and cycling facilities, and undertook a campaign called Share the Road. One factor that supported this intervention was the availability of funds and resources from both central and local government to support implementation. The programme resulted in an estimated reduction of 1149 tonnes of CO_2 emissions between 2011 and 2013, and 34·5 DALYs and two deaths were avoided over the same period.[121]

A cost–benefit analysis conducted in this study showed that the benefits, mainly from improved health and reduced injury, heavily outweighed the costs of investing in active travel, with a benefit-to-cost ratio of 11:1. However, there was only a small reduction in CO_2 emissions. This is because, although the programme was successful in increasing active transport, the scarcity of public transport meant that cycling and walking replaced shorter rather than longer car trips, and therefore had only a small impact on reducing emissions from the transport sector.

The rate of car ownership in New Zealand is about 86% (around 4·3 million vehicles in 2019), one of the highest in the world. New Zealand's political parties have relied on the electrification of vehicles for the reduction of emissions from transport. However, with the high rate of car ownership, this approach alone is not practical.[122] The total population of New Zealand is approximately 5 million, of whom 87% live in urban areas. Assuming the primary target population of such interventions would be those aged 15–65 years (60% of the total population) and that this intervention could be scaled up to the urban population of 2·6 million people that are between these ages, and assuming the same increase of 30% in active travel (equating to the 5·3% decrease in motorised trips across the target population), the programme could result in 20 kilotonnes of CO_2 avoided. This is still far below what would be required for meaningful effects on climate change. Therefore, for interventions to succeed in achieving higher reductions in greenhouse gas emissions, a system change is needed that includes short-term and long-term measures to reduce the use of private vehicles, particularly in urban areas, and increase the use of public transport.

Agriculture, food, and diets

The AFOLU sector contributes around a quarter of global greenhouse gas emissions,[15] mostly arising from CH_4 produced by livestock and CO_2 released by deforestation, with additional contributions from N_2O emissions. The EAT-*Lancet* Commission identified four levers for sustainable land use and food systems: (1) changes in diet, often towards less red meat consumption, increased plant-based foods, and reduced calorie intake; (2) productive and sustainable agriculture; (3) improved land use design, particularly to protect and restore nature; and (4) rapid reductions in food loss and waste. The Commission has estimated that around 11 million premature deaths annually (or over 20% of deaths worldwide) could be averted by 2040 by following a sustainable and healthy diet.[20]

More sustainable diets are typically high in plant-based food and low in animal-sourced and processed foods,[123] and have been shown to have great benefits to human health, increase average life expectancy, and decrease the risk of lung or stomach cancer.[124] The evidence linking consumption of processed meat to adverse health outcomes is robust but a recent review of the evidence linking unprocessed red meat with adverse health outcomes suggested that, although there is some evidence linking the two, the uncertainties are large and there is heterogeneity between studies.[125] This implies that, although the environmental benefits of low red meat consumption are compelling, the health benefits of dietary change might largely result from increased consumption of fruits, vegetables, and whole grains. Dietary shifts could also cut greenhouse gas emissions from the AFOLU sector by more than half and reduce forest loss by 20% between 2030 and 2050 compared with current trends.[126] However, if not properly implemented, sustainable diets can lead to a reduction in intakes of some micronutrients (primarily vitamin B12, calcium, and zinc).[127–129]

Actions to promote productive and sustainable agriculture include changes in farming practices (eg, conservation agriculture, optimising fertiliser use, and nutrient cycling)[130–132] and using technical solutions to reduce emissions in existing approaches (eg, using nitrification inhibitors).[133,134] These actions can substantially reduce greenhouse gas emissions, improve crop yields, and reduce health hazards from agriculture through reduction of emission of hazardous compounds in the atmosphere, soils, and rivers. Measured health impacts of these actions found in our umbrella review were small, possibly reflecting the incomplete knowledge of exposure pathways. Improved land use includes agroforestry (see section on Nature-based solutions), which can sequester soil carbon and thus support climate change mitigation, particularly when compared to land-use changes from less complex systems, such as agricultural monoculture systems that also undermine biodiversity.[135] The Food, Agriculture, Biodiversity, Land-Use, and Energy Consortium is developing a set of sustainable land use pathways for the USA to 2050 that optimise trade-offs between the production (including food and biofuels), conservation, and greenhouse gas targets by 2050.[136] The integration of wider health outcomes and exposures into these models would improve their ability to minimise trade-offs and deliver cost-effective outcomes. Ocean-related actions, such as the reduction of anthropogenic degradation and enhanced restoration of coastal mangroves and seagrass beds, can increase carbon sequestration and benefit local flood protection, livelihoods, and food security but we found no published evaluations of effects on health.[64]

Reduction of food waste could contribute to greenhouse gas emission reductions, particularly in high-income countries where much waste occurs at the retail and household level compared with low-income countries where food loss between harvest and sale predominates. About 88 megatonnes of food are wasted every year in the EU, representing 15–16% of the environmental impact of its entire food value chain and causing annual emissions of 186 megatonnes of CO_2eq. The war between Ukraine and Russia has reinforced the need for strategies to reduce waste, promote dietary change, and improve nitrogen use efficiency (including by planting more legumes) that would reduce greenhouse gas emissions from the food system and increase food security internationally. The reductions in Ukrainian exports of grains and oilseeds could be compensated for by reducing the use of grains to feed livestock by about a third in the EU.[137]

The greatest estimated health co-impact intensities were seen in the AFOLU sector via the diet pathway, which was found to have average reductions in YLL in excess of 300 (ie, 300 years of life gained) per 100 000 people per year (figures 6, 10). Dietary change was also linked with large mitigation intensities (similar in size to the multisectoral policies on average), with particularly large greenhouse gas reductions seen for vegan and vegetarian or pescetarian diets; other actions, such as substituting plant-based foods for animal-based foods, also showed consistently positive health outcomes (figures 6, 10). The wide range of health and environmental impacts from sustainable diets probably reflects substantial variation in their composition.

Mitigation and health co-impact intensities were both the largest in global modelling studies and the smallest in India where average diets already have low greenhouse gas emissions due to low meat consumption.

Shifts in agricultural practices had much smaller mitigation intensities than dietary interventions (with organic farming increasing rather than reducing emissions slightly) and had negligible health co-impact intensities, apart from one study in Brazil that modelled health impacts from dietary changes resulting from reduced meat production. However, it is probable that some shifts in agricultural practices were omitted from the umbrella review because no human health impacts or risk factors were measured, so the included studies might not fully represent the evidence in this area. Similarly, the benefits of organic farming on biodiversity and pesticide use fell outside the scope of this review and organic farming appears to have much lower (or no) environmental benefits when assessments are based only on greenhouse gas emissions reduction.

There is also a growing movement towards the bioeconomy, defined as "an economy where the basic building blocks for materials, chemicals, and energy are derived from renewable biological resources".[138] Such a transition would allow fossil fuel feedstocks for plastics and other products to be replaced by products from renewable biological sources and also embody the principles of circularity (see the section on the circular economy).[139] However, within a bioeconomy, care must be taken to carefully balance food production against the use of natural resources for animal feed and increased use of biomass as fuel. The development of technologies that can minimise trade-offs between food, feed, and fuel and that address the potential for increased emissions from land-use change and bioenergy are key to achieving progress towards a bioeconomy.[140] Assessing the effects of circular economy and bioeconomy approaches on health, equity, and sustainability will be an important priority for future research. These approaches will be necessary to transform society into a net-zero carbon economy.

Pathways to health

Although there were clear differences in mean impacts between sectors, there was also substantial variation within each sector depending on the type of action. Separating the actions by the relevant pathway to health showed that the diet pathway tended to show the largest health co-impact intensities, whereas the largest mitigation intensities were found among actions that also reduced air pollution, although the diet pathway also resulted in large emissions reductions in some studies (figure 11). Actions that addressed the physical activity pathway showed the smallest overall mitigation intensities, probably because they involved short travel distances by walking or cycling (figures 9, 11). Some studies explored health impacts through multiple pathways (air pollution, physical activity, and injuries) without separating the individual health effects. Some of these studies, particularly those in India, found substantial health co-impact intensities through these pathways, although some trade-offs in the form of increased physical injury rates from public transport were also noted. In practice, it is likely that injury rates would be reduced with larger societal transformations towards active travel.

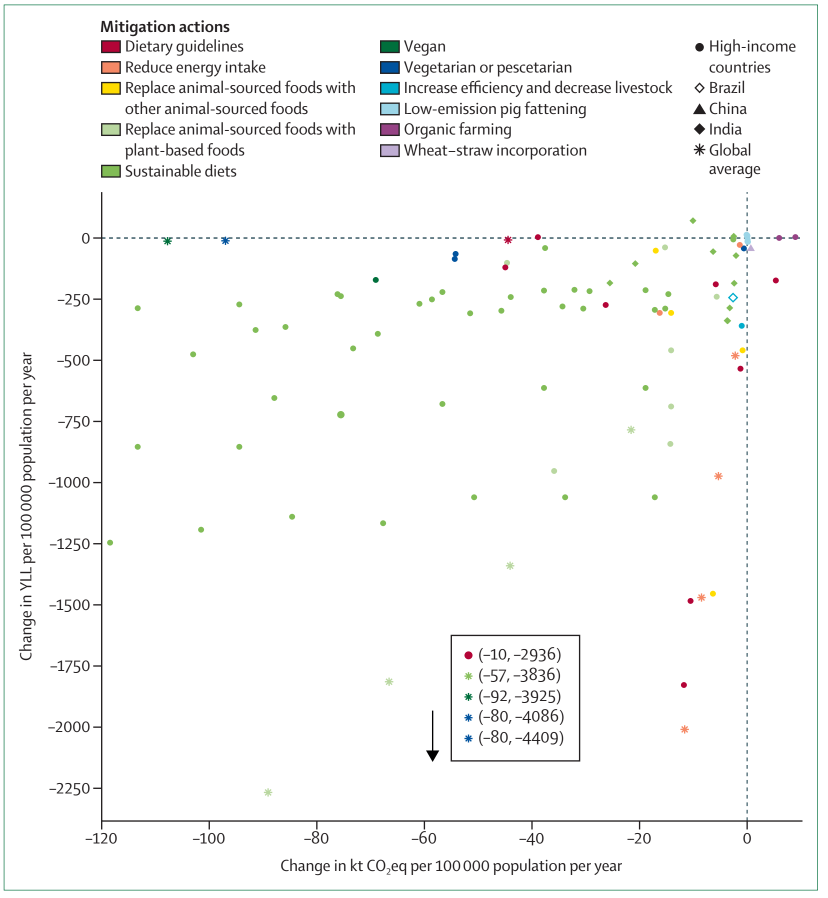

Figure 10: **Climate and human health impacts of mitigation action in the AFOLU sector**
The different-shaped points represent different types of country: circles represent high-income countries; open diamonds represent Brazil; triangles represent China; stars represent global averages; diamonds represent India. Note differences in the vertical scale for changes in YLL when making comparisons between sectors. AFOLU=Agriculture, Forestry, and Other Land Use. $CO_2eq=CO_2$ equivalent. kt=kilotonnes. YLL=years of life lost.

Nature-based solutions

Nature-based solutions (NBS) work to enhance natural or modified ecosystems to deliver biodiversity benefits while simultaneously addressing societal challenges.[68] NBS benefits to human health are achieved largely through enhanced ecosystem services with the pathways linked to regulation of ecosystem processes (figure 12), such as natural hazard mitigation, air quality, climate and disease regulation, the provision of natural resources (including food, water, and timber), and cultural and recreational services to improve mental health and cognition.[142]

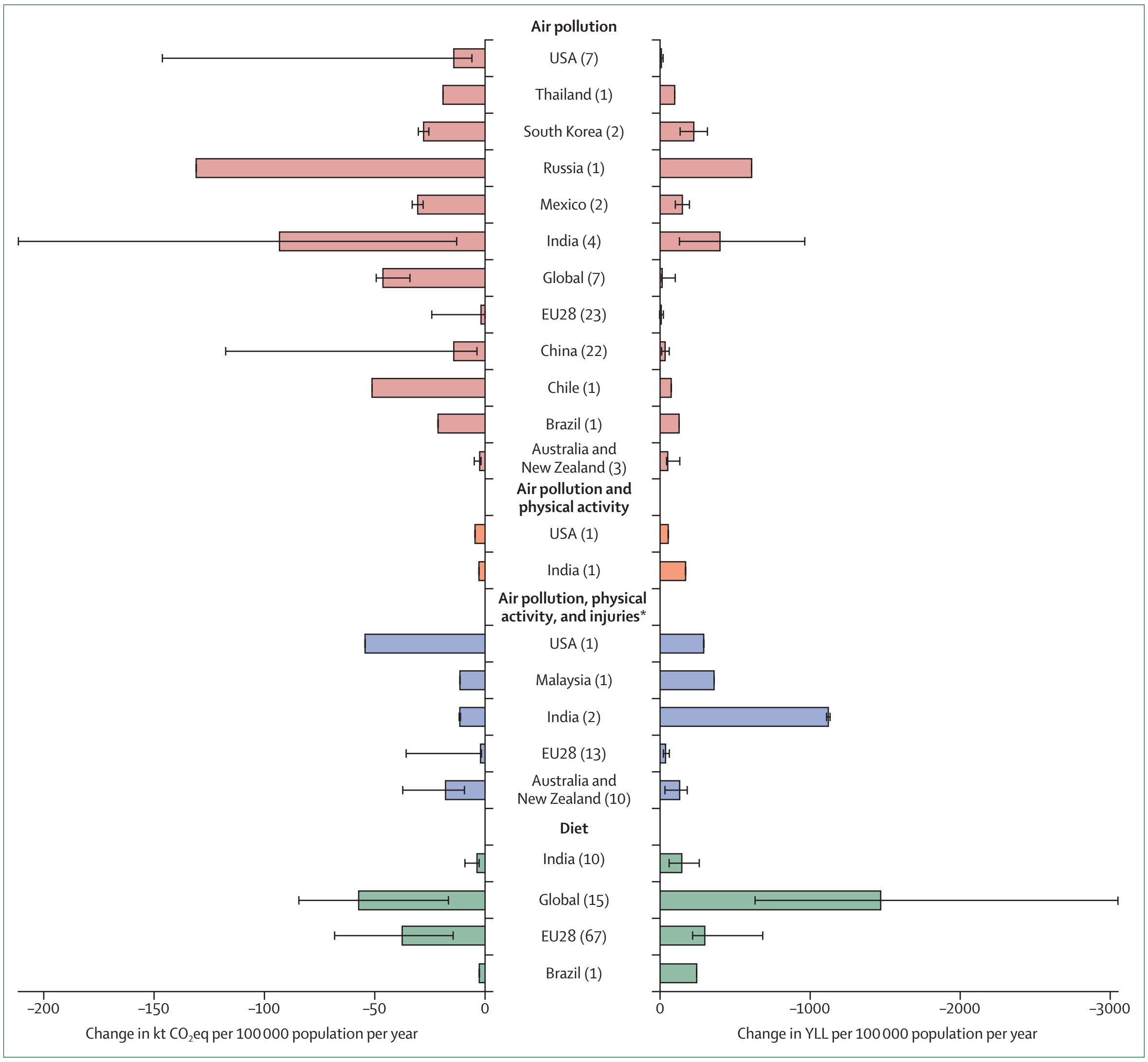

Figure 11: **Variation in carbon mitigation intensity across different health co-impact pathways**
The figure presents the median change in kt CO_2eq per 100 000 population per year and the reduction in YLL per 100 000 population per year compared with business as usual, split by country context. The black bars represent the IQR for estimates. The number of actions is given in parentheses. CO_2eq=CO_2 equivalent. EU28=all 27 countries of the EU plus the UK. kt=kilotonnes. YLL=years of life lost. *The pathway is a combination of two or more of air pollution, physical activity, or injuries.

Natural climate solutions are a subset of NBS that can be used to limit heating through reducing atmospheric greenhouse gas concentrations by reducing greenhouse gas emissions or increasing carbon sinks, or both.[143,144] They comprise three broad approaches: (1) protecting ecosystems (eg, by halting tropical deforestation); (2) restoring ecosystems, such as wetlands or community forests; and (3) sustainable landscape management across crop and grazing lands and urban ecosystems.

Recent estimates suggest that well designed and implemented NBS have the potential to deliver cost-effective annual emission reductions and removals of 5·0–11·7 gigatonnes of CO_2eq by 2030, rising to 10–18 gigatonnes of CO_2eq by 2050;[145] these estimates are usually cost-constrained at US$100 per tonne of CO_2eq to account for the cost of global production of food and wood, the respecting of land tenure rights, and sufficient biodiversity conservation.[143] NBS have also gained societal and political support because of their potential to deliver multiple benefits, including achieving global development objectives set out in the Sustainable Development Goals[145] by offering many win-win strategies for addressing climate change adaptation, safeguarding human health, and stemming biodiversity loss.[146] A key concern surrounding NBS implementation is ensuring appropriate safeguards to protect the rights of Indigenous and other local communities and to minimise harmful trade-offs.[145,147]

There is a scarcity of quantitative evidence on the full range of pathways by which actions can achieve significant mitigation and health benefits. No systematic reviews of

	Forests	Rivers and watersheds	Farmland	Cities	Coasts and oceans
Example of solutions	Protect, restore, or sustainably manage forests through REDD+ initiatives	Restoration and protection of wetlands and peatlands	Agroforestry: integrated land management (eg, growing trees and crops or grazing animals on the same land)	Green infrastructure: harnessing and integrating nature and natural systems in urban infrastructure (eg, parks, green walls or roofs)	Protect and restore wetland and marine habitats, such as mangroves, coral reefs, seagrass, and kelp forests
Mitigation action	Increased uptake and storage of carbon from the atmosphere Prevention of further emissions from decomposition and wildfires	Enhanced carbon sinks through sequestration and storage Avoidance of methane emissions from intact wetlands	Enhanced carbon sinks through sequestration and storage Improved productivity means less land use and disturbance, and reduced fertiliser use	Enhanced carbon and surface ozone sequestration Reduction of urban heat island effect leading to reduced energy demand through passive cooling	Enhanced storage of both blue and green carbon through sequestration Avoidance of methane emissions from intact wetlands
Health co-benefits	Livelihood benefits and poverty reduction (eg, from sale of non-timber products) Gender participation and equality Enhanced forest ecosystem services (eg, flood protection and regulation of zoonotic diseases and air quality)	Natural water quality improvement reducing occurrence of algal blooms Enhanced wetland ecosystem services (eg, flood control) Reduced poverty from income generation through recreation and tourism	Increased crop yields and food security Livelihood benefits and income diversification from sale of timber Enhanced local microclimates generating a cooling effect Improved hydrological cycles and water catchment, and increased flood protection	Reduced heat-related deaths and morbidity Reduced storm water run-off buffers against extreme rainfall events Removal of harmful air pollutants Recreational spaces increase physical activity, reducing incidence of cardiovascular disease and improving mental health	Livelihood benefits and income diversification from fishing and sustainable building material Increased food security and key sources of protein Natural barrier to limit the impact of floods, storms, and sea-level rise Marine ecosystems are a novel source of pharmaceutical compounds

Figure 12: **Pathways to health and equity from nature-based solutions**
The pathways were adapted from the Global Commission on Adaptation.[141] REDD+=Reducing Emissions from Deforestation and Degradation.

NBS that deliver mitigation and health co-benefits were identified. A search for individual actions found piecemeal evidence across multiple habitat types and that mitigation potential and pathways to health vary greatly by type of action undertaken. In total, 26 studies linking modelled and implemented NBS with health exposures and outcomes were identified (appendix pp 15–25), of which six were based on implemented data. Many studies describe the potential for green spaces, such as urban trees to deliver climate and health outcomes, but the mitigation potential of such actions is relatively low compared with the estimated scale of mitigation from the protection and restoration of intact ecosystems, and improved agroforestry and land management for food production.[146,148]

Urban trees

Several studies documented how the sustainable management of urban trees can improve air quality and deliver greenhouse gas mitigation, estimated either as carbon sequestration, carbon storage, or avoided emissions (the latter is typically achieved by reducing energy usage). All the studies were conducted in North America and Europe and were a mixture of ecosystem assessments (field visits) and modelling exercises using i-tree software (appendix pp 15–25). The effectiveness of pollutant uptake, mitigation, and energy savings varied by species; consideration of species is needed to optimise benefits, including to enhance biodiversity while minimising potential trade-offs, such as O_3 production, increased allergies, and altered dispersion of pollutants.[149] Although the evidence base for the mental health benefits of access to greenspace is large,[150] no studies linking the provision of greenspace with mental health co-benefits and greenhouse gas emission reductions were identified.

Air quality

Urban trees in California, USA, are estimated to sequester or help avoid 8·5 megatonnes of CO_2 per year, of which 1·3 megatonnes were from avoided emissions from building energy savings due to the cooling effect from trees (see the section on Energy savings).[151] This total mitigation impact is equivalent to the removal of 1·8 million cars from Californian roads.[151] Alongside this effect, a net air pollutant uptake of 3537 tonnes per year is estimated as the difference between uptake of PM_{10}, NO_2, sulphur dioxide, and O_3 and the emission of biogenic volatile organic compounds (BVOCs), which can act as precursors to local ground-level O_3 pollution, as trees can both remove and contribute to tropospheric O_3 formation.[152] The value of air quality improvements (ie, the value that society places on clean air) is estimated at $56·2 million,[151] although this is probably an underestimate of the true benefit of cleaner air; a previous study estimated the air quality benefits attributed to Californian trees as $446 million, which is the cost of avoided mortality and care of acute respiratory diseases.[153] There are an estimated 5·5 billion urban trees in the USA, with 343 million urban trees in California, making it among the top five states, alongside Florida, Georgia, North Carolina, and Texas. Analyses showed that California has the greatest pollution removal values by urban forests ($639 million per year) and a high estimated carbon sequestration by urban forests (2·9 million tonnes of carbon per year) compared with other states in the USA.[154]

Energy savings

Urban trees alter energy use in buildings and associated emissions from power plants by shading buildings, cooling air temperatures, and altering wind speeds around buildings.[154] This results in electricity savings from cooling, natural gas savings from reduced heating needs, and avoided emissions of air pollutants from power plants and space-heating equipment.[151] Regional variation in the extent of energy savings was apparent: for instance, street trees in Lisbon, Portugal, had an estimated energy saving of US$6·16 per tree per year;[155] the equivalent was an average of $13 per tree per year across five US cities,[156] and energy savings were valued at $36 per tree in Toronto, Canada.[157] This variation was attributed to tree species, building characteristics, climatic zones, and meteorological data used in the estimates.

Unintended consequences of urban trees

Even well intended mitigation actions, such as planting urban trees, can have unintended consequences that exacerbate inequalities. Although urban trees can provide a range of benefits to the environment, human health, and wellbeing,[151] studies also suggest that access to these benefits is often unequal, and some groups can benefit more than others.[158] For example, urban trees can increase property values[151] and, if distributed unevenly, might lead to green gentrification and make land inaccessible to low-income residents (similar considerations could apply to other actions that bring environmental benefits to neighbourhoods). The term green gentrification or environment gentrification is used to describe the influx of affluent residents to low-income neighbourhoods in part due to greening initiatives.[159] Green climate gentrification has been documented in cities in North America, Spain, Belgium, and South Korea.[159] Tree pollen and the emission of BVOCs from urban trees is also well reported in relation to potential health effects, such as exacerbation of allergies, asthma, and rhinitis symptoms.[160]

Protecting and restoring ecosystems

The protection and restoration of community forests can also deliver human health and wellbeing benefits, such as food, nutritional security, and livelihood benefits. These are implemented solutions by rural subsistence farmers in low-income and middle-income settings, whose livelihoods improved through income generation of surplus produce or by taking part in international carbon trading that allows high-income countries to purchase emissions offsets from LMICs to reduce overall greenhouse gas emissions. For example, an investigation of the impact of a climate-compatible development project in Malawi found a 50-year mitigation potential of 4·5 megatonnes of carbon sequestration, which was attributed to implementation of ecosystem-based actions (eg, conservation agriculture) and forestry activities (eg, woodlot regeneration), alongside other actions such as improved cookstoves and access to loans.[161] Human wellbeing benefits were linked to increased income, enhanced crop yields, improved nutrition, and improved asset protection from extreme weather due to regeneration and adaptation activities, although the benefits were not equally distributed across groups. A study in rural Ethiopia assessed the impact of implementing a Clean Development Mechanism project (a UN-run carbon offset scheme) aimed at increasing carbon sequestration, reducing poverty, and improving ecosystem restoration. The project used farmer-managed natural regeneration, which regenerates native trees across agricultural landscapes and community forests,[162] and was estimated to sequester 165 000 tonnes of CO_2 and generate $726 000 over the first 10 years. Local environmental regeneration also led to an increase in provisioning services, such as fodder, wild fruits, and non-timber forest products, as well as improvements in ground water availability and local micro-climatic conditions.[163]

Reducing Emissions from Deforestation and Degradation (REDD+)

The REDD+ framework is aimed at slowing, halting, and reversing forest cover and carbon loss through five activities: (1) reducing emissions from deforestation; (2) reducing emissions from degradation; (3) conservation of forest carbon stocks; (4) sustainable management of forests; and (5) enhancement of forest carbon stocks.[164] An assessment of the mitigation and adaptation potential of a REDD+ project in Nepal found implementing community forests increased annual carbon sequestered by an estimated 5·1 tonnes per hectare.[165] Project activities included the promotion of alternative energy (eg, improved cookstoves) to reduce extraction of forest resources, encouraging plantation activities in sparse forest areas and uncultivated private land (provision of seedlings and support), raising awareness on sustainable harvesting practices, control of illegal harvesting, and implementing income-generating activities in poor households. Improvements in livelihoods were linked to income-generation activities, selling products from forest-based cottage industries, and from the sale of non-timber forest products and livestock, which were increased due to the new plantations. Other benefits included an increase in social capital, enhanced coping during adversity, and reduced inequities through enhanced benefit-sharing that targets livelihood improvements for the most deprived, including of food supplements (eg, roots, tubers, fruits, flowers, and shoots). However, the authors warn (but did not empirically examine) that poorly managed REDD+ projects that prioritise carbon mitigation could limit vegetation richness and compromise nutritional diversity and climate resilience.[165]

Consistent participation in local communities of both men and women throughout REDD+ processes is crucial. REDD+ projects have been repeatedly criticised by reports of inequity across three key dimensions: (1) contextual equity: the conditions embedded in the social and political context that put some people or groups at a disadvantage (eg, Indigenous communities or poorer members of traditional communities); (2) procedural equity: the level of representation, participation, and equal say in decision making processes; and (3) distributive equity: the distribution of costs and benefits of policies and actions among stakeholders.[166] A review of rights abuses from REDD+ has highlighted multiple allegations about possible welfare impacts on forest-dependent (especially Indigenous) peoples.[164] These impacts can be due to the implementation process of the action or from the pre-existing local context (eg, unclear or inequitable land laws). Implementation guidelines are improving with a renewed focus on the central role of Indigenous peoples in climate change initiatives and protecting forests.

Health-care provision case study: Health in Harmony, West Kalimantan, Indonesia

More than 60% of lowland forests within protected areas in Borneo's West Kalimantan region were lost to illegal logging in the 15 years between 1985 and 2001. The non-profit organisation, Health in Harmony, through extensive consultation with local communities, identified the costs of health-care access as a key driver of illegal logging and unsustainable forest use. This includes cost of the care itself, transportation to health-care services, the cost of food and housing while away from home, and the loss of income while sick. The need to pay for these costs can lead families to overexploit the environment themselves or make deals with outsiders to do so. Health in Harmony, in close partnership with the district government and the national park management, established a local health clinic that provided accessible health-care services by allowing for non-cash payment and discounts on care on the basis of the amount of logging in each community. Conservation programmes, educational programmes, and alternative livelihood trainings were also offered.[167]

The health clinic was accessible to both the communities who did and did not participate in the intervention as it was unethical to deny access to health care on the basis of participation. The intervention provided health-care access to more than 28 400 patients across all communities, although clinic usage and patient visitation frequency were highest in communities participating in the intervention. From 2007 to 2012, infant mortality declined from 3·4 to 1·1 deaths per 100 households. This was reflected in significant declines over time in diagnosed cases of malaria, tuberculosis, childhood-cluster diseases, COPD, and diabetes in all communities. Diagnoses of neglected tropical diseases increased over the course of the intervention (driven by an increase in leprosy diagnoses), perhaps due to increased health-seeking behaviour by the communities affected by the intervention. Consultations for lower and upper respiratory infections and dental diseases increased across all communities over the study period but increased significantly less in intervention communities.[167,168]

The intervention led to a 90% reduction in the number of households relying on logging as a primary income source. It prevented an estimated 27·4 km² of deforestation in the national park in 2008–18, an approximately 70% reduction in annual forest loss compared with the equivalent period in 2001–07. This reduction in forest loss was estimated to have prevented 590 000 tonnes (90% CI 270 000–1 130 000) of above-ground carbon loss. This number might be an underestimate because the project has also promoted the regeneration of secondary forest and the impact of prevented losses of below-ground carbon has not yet been quantified.[167]

A major factor in the success of this intervention was that it was designed by the community, and it provided multiple cross-sectoral solutions simultaneously in response to the problems identified in the community (ie, they required access to health care, but also education programmes and training on sustainable livelihoods). Those communities that engaged with the intervention (assessed by total individual contact across all intervention activities, such as clinic visits, attending meetings, education activities, or livelihood training) showed a significant decrease in forest loss, whereas medium-engagement communities showed no change and the least-engaged villages showed an increase.

For more on **safeguards in the REDD+ framework** see https://redd.unfccc.int/fact-sheets/safeguards.html

"Poor access to health care has been shown to be a main driver for ecosystem degradation in other parts of Indonesia (eg, Bukit Baka Bukit Raya National Park), and in Madagascar, the Philippines, and Brazil. Other organisations that have used the same or similar techniques (ie, the Radical Listening approach to understand community priorities) in other parts of Indonesia, and in Malaysia, Mozambique, and Rwanda have also found health-care access to be one of the main drivers" (Webb K, Health in Harmony, personal communication). Therefore, scale-up of this intervention would require providing affordable access to health care, as well as extensive engagement with the local community to identify the main drivers of illegal logging and the services needed to avert such practices.

Pathways to a just and equitable net-zero transition

Climate-resilient development

Societies will need to both adapt to climate change that cannot be prevented and cut emissions urgently to reduce the risks of climate change. Rapid cuts in greenhouse gas emissions will reduce the magnitude of adaptation responses required to protect health and make it less likely that the limits to adaptation will be reached. Some adaptation actions can make mitigation more challenging; for example, increasing uptake of air conditioning will increase energy demands and potentially increase fossil fuel dependency. By contrast, passive ventilation, cool roofs, and increasing greenspace in cities can reduce energy demands and reduce extreme heat exposure, although might require increased water consumption. Although mitigation and adaptation actions must increasingly be integrated, there are few documented examples of integrated actions to guide policy and practice.[67] In our review, we found piecemeal evidence of implemented green infrastructure with quantified assessment of mitigation, adaptation, and health co-benefits (appendix pp 15–25). Overall adaptation actions have rarely been evaluated to assess their health effects, particularly in LMICs.[169] Climate funders, policy makers, and researchers should scale up endeavours to integrate and evaluate the effects of climate action at scale. Deep decarbonisation to achieve climate mitigation goals will require transformation at a societal level. This includes transforming economic systems and relationships, and the ways in which we conceptualise and measure societal goals.

For an **overview of carbon pricing initiatives** see https://carbonpricingdashboard.worldbank.org/

Carbon pricing

Carbon pricing can include carbon taxes, emissions trading schemes, and carbon credits, as well as fuel taxation and the withdrawal of subsidies. Such mechanisms and policies can be cost-effective in reducing greenhouse gas emissions and can potentially have important effects on health through pathways such as improved air quality, encouraging active travel, the redistribution of wealth, and raising funds for health care.[170] Carbon pricing interventions can be implemented across all sectors, including energy, buildings, transport, and food. They can also potentially cover a range of greenhouse gases. However, there is the potential for carbon pricing mechanisms to lead to negative health and wellbeing outcomes, especially if socioeconomic inequalities are exacerbated.[171]

Production subsidies are tax breaks or direct subsidies that reduce the cost of producing fossil fuels. Consumption subsidies reduce the price to the consumer. There are different approaches to estimating fossil fuel subsidies depending, for example, on whether public financing of fossil fuels (such as that from state-owned enterprises) are included. A recent International Monetary Fund working paper includes implicit subsidies that incorporate the valuation of damages from air pollution and climate change, together with foregone consumption taxes. This approach results in $5·9 trillion in estimated subsidies or 6·8% of global gross domestic product (GDP) in 2020, probably increasing to 7·4% of GDP by 2025. Only about 8% of this value reflected undercharging for supply costs (explicit subsidies). The remaining 92% (implicit subsidies) reflects the difference between actual prices and the so-called efficient prices required to account for the resulting damages.[172] This makes a compelling case for implementing carbon prices at a level that reflects both emission-reduction targets and the co-benefits of decarbonisation. However, the barriers to implementation include powerful opposition from some fossil fuel companies, concerns about job losses, and the effects of unabated energy prices.[173]

Carbon pricing, which in 2022 covered 23% of global emissions, often at low levels, is insufficient on its own to drive deep decarbonisation and the systemic transformation it requires.[174] However, in coordination with other policies, carbon pricing is a key component of transformative and ambitious mitigation strategies. Health co-benefit assessments could support the implementation of effective carbon pricing policies as part of coordinated, transformative policy strategies. A literature mapping exercise was undertaken as part of a systematic review of studies on carbon pricing and health,[175] showing different ways in which health co-benefit assessments can inform carbon pricing design and implementation.

Evidence on the magnitude of health co-benefits and their monetised value can provide more accurate estimates of policy costs, optimal or efficient price levels,[42,176] or the price levels at which the economic costs of the taxes are fully offset by co-benefits, implying net-zero costs. In the USA, monetised human health benefits from improved air quality can offset between 26% and 1050% of the cost of US carbon policies, depending on context and assumptions.[177,178] Another study of energy supply, based on the value of a statistical life approach, shows that the global ratio of the value of health co-benefits to mitigation costs ranges from 1·45 to 2·19. India and China show easily the largest co-benefits, although these estimates are dependent on the coefficient used for the value of a statistical life.[179]

The use of revenues from carbon pricing is another possible pathway for health promotion and equity. Using revenues for income compensation can address the potential food insecurity trade-offs in low-income countries.[180] Other suggestions include directing revenues to improve access to and affordability of renewable energy, subsidising healthy foods,[180] and funding universal health coverage, public transportation, or insulation for low-income households.[181] Revenue-neutral intervention designs that subsidise low-emission food groups can result in negative health impacts in high-income countries—eg, because of increased consumption of sugar and soft drinks—showing that climate and health co-benefits do not always move in the same direction.[182]

Other specific features of emissions trading schemes, such as market scale and the allocation of initial allowances, also have health impacts. For example, in China, larger emissions markets (at a regional or national level as opposed to provincial) were associated with lower co-benefits, especially in areas that become net purchasers of allowances.[183] Geographical tax differentiation and exemption of key commodities have been explored as mechanisms to enhance health co-benefits and mitigate adverse effects in vulnerable regions.[180] Some studies find that tax differentiation can promote health co-benefits, increasing air quality and diet-related outcomes while reducing food security trade-offs, at a small cost in terms of mitigation effectiveness.[180] Countries such as Brazil, which are land-rich but also have a high proportion of emissions from land use, could reduce their agricultural emissions through carbon pricing without significantly impacting food security. By contrast, in countries such as China and India, which have high population densities, agricultural mitigation would lead to substantial food calorie loss with little contribution to global greenhouse gas mitigation, depending on crop substitution assumptions.[184] Increasing soil carbon sequestration on agricultural land could reduce projected calorie loss from carbon prices compatible with 1·5°C targets by 10%, as more land would remain under agricultural production, while also benefiting from yield increases due to improved agricultural land management.[184]

Interactions of carbon pricing with other policies also affect health co-benefits. These interactions can be highly context-specific, but complementary policies, such as sugar taxation or soil carbon sequestration, can enhance co-benefits by directing demand substitution away from harmful products or enhancing food security.[178,182] Similarly, some carbon pricing policies add little to realised health co-benefits, for example if substantial mitigation action has already delivered large health gains. Understanding these interactions can help to design policy packages that leverage the potential for co-benefits while avoiding double-counting and protecting the most vulnerable populations.

Although carbon pricing, overall, is found to deliver large health co-benefits, existing geographical and socioeconomic health disparities can sometimes be exacerbated, with uneven distribution of benefits and, in some cases, negative impacts for specific areas or population groups. Most existing evidence of trade-offs focuses on potential food insecurity impacts.[180,182] Some studies also suggest that carbon cap-and-trade programmes (used interchangeably here with emissions trading schemes) can lead to localised increases in emissions as a product of permits trading.[185] An improved understanding of these and other potential trade-offs is indispensable for the adequate design of compensatory and redistributive policies that include targeted subsidies or income transfers, and complementary local emissions regulations. A well designed carbon tax might avoid some of the potential inequities arising from cap-and-trade programmes.

Carbon pricing case study: reassigning fossil fuel subsidies to health care

Policies that reassign revenues from fossil fuel subsidies can accelerate the shift to renewable energy generation while increasing investments in health care, education, infrastructure, or other social services that benefit vulnerable populations. Reassigning funds to health care in the form of providing free medicines or diagnostic tests can provide tangible benefits in the form of economic returns.[181] Indonesia is among several countries that allocated large sums of fossil fuel subsidies to finance health care and other social services.[186] It is regarded as a success, although the country was faced with backtracks in recent years.[187] Recent fuel subsidy reforms demonstrate how, through public information campaigns, a timely implementation, and roll-out of social programme compensation schemes, violent protests and oppositions can be circumvented. The example from Indonesia shows that reassigning revenues from fossil fuel subsidies to health care can provide opportunities for climate mitigation and health. It is important for governments to implement redistributive policies and address potential adverse effects of the reforms for low-income households to ensure that the most vulnerable populations benefit from these policies.[187]

Circular economy approaches

A significant gap is evident on the health and greenhouse gas effects of circular economy and bioeconomy strategies.[139,188] They are both potentially important contributors to greenhouse gas mitigation because consumption-based emissions embodied in traded goods and services increased from 4·3 gigatonnes of CO_2 in 1990 (20% of global emissions) to 7·8 gigatonnes of CO_2 in 2008 (26%).[189] The 2022 Circularity Gap report has estimated that the current world economy only cycles 8·6% of the resources it uses, leaving a so-called circularity gap of more than 90%.[190] According to the report's estimates, global circularity declined from 9·1% in 2018 to 8·6% in 2020 and, in 2019, 100 gigatonnes of resources were consumed. This inefficient and wasteful use of resources contributed to climate change and to increasing risks of breaching several other planetary boundaries.

In a departure from the traditional linear economy that aims to encourage increasing consumption of products from primary materials, the circular economy is a model of production and consumption that involves sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products as long as possible. In this way, the lifecycle of products is extended.[191] The circular economy offers potential benefits to businesses and society, including through reduced demand for primary materials, reduced waste, and reduced greenhouse gas emissions. When a product reaches the end of its life, the materials are kept in a closed-loop system and create further value. Despite the major contribution of circular economy approaches to climate change mitigation, in the run up to the 26th UN Climate Change conference, only a third of all nations had any mention of the circular economy in their NDCs under the Paris Climate Agreement, and fewer than 40% of these pledges included any plans for training to support implementation.[190]

A systematic review has assessed the contribution that circular economy and related approaches could make to climate change mitigation.[192] The authors identified 341 relevant studies, grouped into six partly overlapping sectors (industry, waste, energy, buildings, transport, and agriculture). In common with our findings, the authors concluded that few of the articles discuss implementation processes, the importance of contextual factors, or the need to explicitly address equity considerations and poverty alleviation. The estimates of greenhouse gas reductions are wide-ranging, depending on sector and context. The largest savings are in the industry, energy, and transport sectors; mid-range savings are estimated in the waste and building sectors; and the lowest gains are projected in agriculture.[193] Some large greenhouse gas savings were observed for specific actions (eg, 60–90% from the recycling of iron and concrete).

There has been little systematic assessment of the health effects, which could be both beneficial (eg, reduced air pollution from less waste burning and more efficient use of resources, more affordable food from reduced food waste, and savings to health systems from more efficient resource use freeing funds for health care) or harmful (eg, increased exposure to toxic chemicals from poorly regulated recycling of electronic waste). A report from the WHO Regional Office for Europe discussed the potential pathways by which circular economy approaches could impact health, including exposure to toxic chemicals from e-waste or use of contaminated sewage sludge containing pesticides, pharmaceuticals, or heavy metals in agriculture. It suggested actions that could reduce risks and capitalise on opportunities, including improved occupational health programmes for at-risk workers and regulation of informal waste dumps and recycling facilities.[188]

However, the circular economy is not fully transformative as it does not explicitly reduce the demand for goods. Instead, it assumes reduction in consumption of raw materials through recycling,[194] but resources can only be dissipated, which increases losses in quantity and quality, or converted, which requires new materials and energy.[195] There are limitations in conserving materials through successive re-use cycles, which result in leakage from the system,[196] and there are potential spillovers of the net-zero emissions economy and increased emphasis on circularity of materials. For example, e-waste is often exported to low-income countries where regulation is weak and implementation of existing regulations is poor. In 2020, the UK generated 23·9 kg of e-waste per person (the second highest amount in the world), much of which is exported, mainly to Ghana and Nigeria.[197,198] One example is the community of Agbogbloshie, an informal community in central Accra, Ghana, where e-waste is recycled in unregulated circumstances, resulting in grossly polluted living and working conditions. Population studies show high levels of heavy metals and toxins in blood samples, which are particularly hazardous to neonates. Breast milk samples from women residing near the Agbogbloshie market contained elevated concentrations of polychlorinated biphenyls and brominated flame retardants.[199] Balanced assessments of the net-zero economy should encompass potential spillovers and other harms that can undermine prospects for a just and equitable transition.

Transformative actions to a healthy and net-zero carbon future

The need for demand-side policies to reach net zero

There are increasing calls for transformational change, with the recognition that net zero (and other sustainability goals) cannot be achieved within existing dominant social and economic systems, because they are themselves the cause of the climate crisis.[200,201] For example, global emissions in the housing sector[15] and total emissions from transport in European countries[202] both show that efficiency gains (per unit of habitable surface and per km travelled) have been significant, but these have been more than offset by growing emissions linked to increasing demand (ie, growth in floor area per capita and passenger-km travelled [1 passenger-km represents 1 km done by one passenger]). In both cases, the switch to cleaner sources of energy has had a positive, although marginal, role in bringing emissions down. In the case of housing, global emissions have continued to increase by 5% between 2010 and 2019 despite this sector being targeted by 27% of the NDCs submitted under the Paris Climate Agreement.[15]

A similar trend can be seen in the case of transport in Europe. Passenger transport emissions in Europe increased by 12% between 1995 and 2019.[202] Transport demand in Europe (measured in terms of passenger-km) increased by 31% in the same period and constituted the main driver of emissions, more than offsetting emissions reductions from increased energy efficiency and changes in load factors (figure 13). Average car occupancy in Europe also decreased. Modal shift contributed to increasing emissions by 2%, due to general shifts away from public road transport to cars and aircrafts.

Policies and actions need to go beyond solely improving efficiency (mostly via technological change), while leaving in place systems that are unsustainable. Current systems lead to high demand for energy and materials and thus high emissions, while failing to provide healthy environments or promote thriving livelihoods.[11,12] The most recent IPCC Working Group 3 report on mitigation highlights the need for "systemic infrastructure changes that enable behavioural modifications and reductions in demand...that can in turn reduce energy demand".[15] These so-called sufficiency policies are defined as "a set of measures and daily practices that avoid demand for energy, materials, land and water while delivering human well-being for all within planetary boundaries".[15] In line with these findings, the latest IPCC report brings attention to the need for policy packages, which combine ambitious demand reduction, efficiency, and renewable energy measures.[15]

However, actions on demand reduction are often at the margin of climate mitigation policy frameworks, net-zero scenarios, and efforts to measure and estimate health benefits. These scenarios are mainly built on integrated assessment models, which combine concepts from climate science and economics into a single modelling framework.[203] Despite being criticised in the literature as they "do not consider the global cost of reaching any particular temperature or emissions target and rely on assumptions which, when altered, provide widely varied estimates",[204] these scenarios are the only long-term scenarios submitted by the scientific community to the 2022 IPCC report on climate mitigation.[204,205] Such scenarios tend to be heavily focused on efficiency gains. For example, Chapter 7 in the sixth assessment report of the IPCC Working Group 3 reviews the mitigation policies within the AFOLU sector, including in integrated assessment models. Of these, only reducing deforestation and degradation would potentially qualify as a demand-reduction strategy but the IPCC does not propose how this could be achieved.[15]

Capturing the full mitigation potential through implementing demand reduction is one of the important research gaps identified in the literature.[11] Outcomes from the studies evaluated as part of this project show that, for the umbrella review, many studies model health co-benefits from demand-reduction outcomes when compared with efficiency gains (128 studies on demand reduction compared with 62 studies on efficiency, with seven unclassified). However, many of these studies show no mechanism of action; that is, they assume a shift to demand reduction without specifying how it is achieved. Evidence on the health co-benefits possible from achieving transformational change is sparse across the literature base. A systematic review of transformations for climate mitigation in 2021 found that less than 10% of the 198 articles reviewed mentioned health or health-related co-benefits.[206] Therefore, modellers should consider the emerging multidisciplinary literature on policy packages, which examine how policies could be combined to trigger the systemic changes needed to decarbonise the global economy and to ensure both the implicit and explicit system change will occur.[207,208]

A systems approach to demand reduction for climate and health benefits

Realising the potential of demand-reduction actions to also deliver significant health benefits calls for exploring new policy approaches and implementation strategies. Results from the umbrella review reveal that large and widespread changes in behaviour patterns will be required to achieve climate and health benefits at the scale needed for the attainment of the Paris Climate Agreement goals. We define transformative change in the context of this report as systemic social change that enables the achievement of the highest possible level of health for all people at net-zero greenhouse gas emissions. If we take a broader planetary health perspective, this could be extended to systemic social change that enables the achievement of the highest possible level of health for all people within planetary boundaries. A greater focus on systemic transformation can potentially trigger the behavioural change needed for bringing both climate and health benefits at scale.[206] This will be a major focus for the second phase of the Pathfinder Initiative.

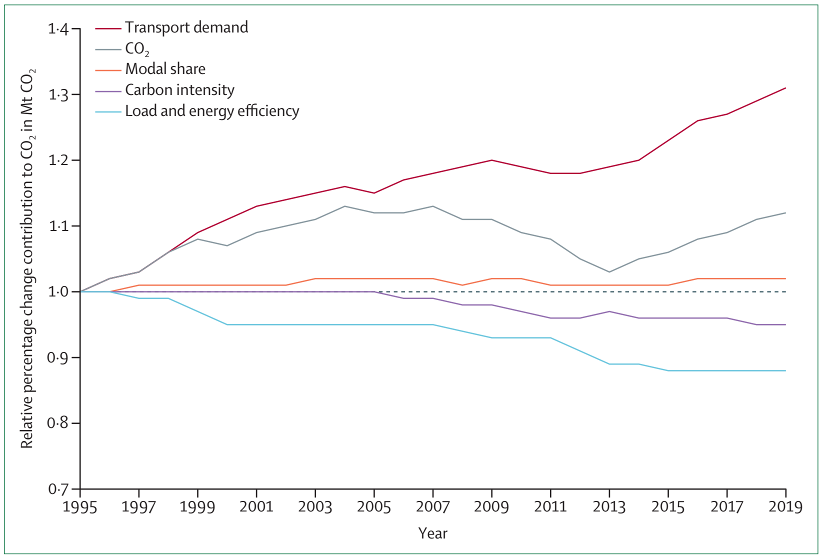

Figure 13: **Drivers of CO_2 emissions in the European transport sector**
Decomposition of the driving factors behind CO_2 emissions from EU passenger transport, from 1995 to 2019. CO_2 emissions are a product of transport demand, modal share, load factor of vehicles, energy efficiency of vehicles, and carbon intensity. Mt=metric tons. Reproduced with permission from Enerdata.[202]

Transformative change case study: Irish transport sector

Understanding what policies can bring systemic change (ie, change the system structure) to trigger large behavioural change can help to achieve both the climate goals of the Paris Climate Agreement and improvements in health equity. A first step is to map the dynamics characterising the current systems that lead to unsustainable results (eg, poor health, high emissions, and unequal access to services and opportunities). In 2022, the OECD mapped the Irish transport sector using their Systems Innovation for Net Zero approach.[209] Growing car use and its related emissions and negative effects were identified as being largely determined by car-dependent transport and urban systems organised around increased mobility and characterised by three unsustainable dynamics: induced car demand, urban sprawl, and the sustainable modes low-attractiveness trap. Within the OECD framework, once the system is

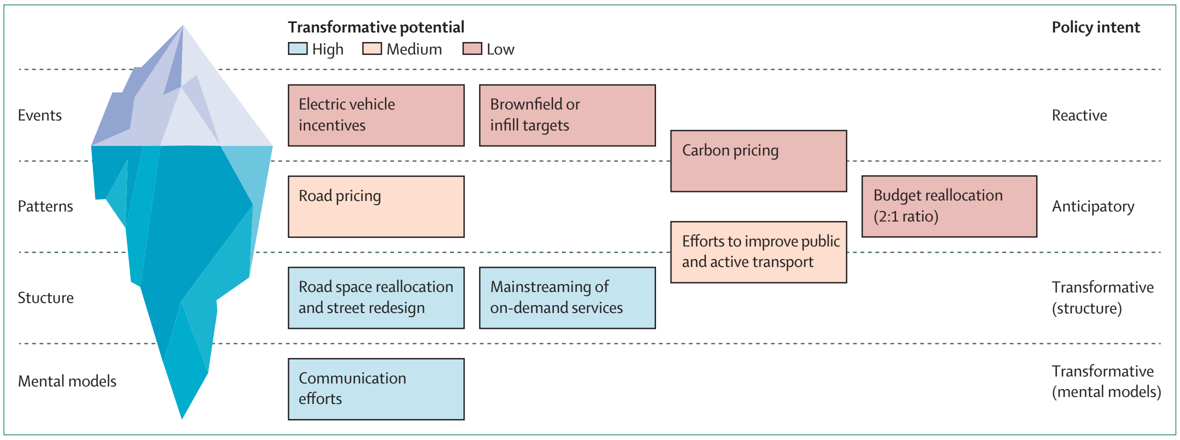

***Figure 14:* Proposed Irish transport policies classified by transformative potential and intent**
The classification of the transport policies was done using the Systems Innovation for Net Zero approach. In short, this is a three-point process to (1) envision the goals of a well functioning system and challenge the mental models guiding systems towards different ends; (2) understand why the current systems are not achieving envisioned goals and assess the potential of implemented and planned policies to redesign the system; and (3) prioritise and scale up the policies with a capacity to redesign systems so that patterns of behaviour are altered and the desired results emerge. Budget allocation refers to the investment allocation ratio between public transport and road infrastructure. Reproduced with permission from the Organisation for Economic Co-operation and Development.[209]

mapped, the next step is to identify transformative policies by analysing: (1) the intent of a given policy (ie, whether it aims to anticipate and cope with car-dependent systems, or whether it aims to transform the system and encourage a shift away from car dependency; figure 14); and (2) the potential for policies to transform the structure of the car-dependent system, explicitly by reversing the three dynamics identified as characterising the car-dependent system (appendix pp 27–29).

The result of the policy assessment applied to Ireland's transport system indicated three focal areas to address for transformative change: (1) road space reallocation, the scaling up of on-demand shared services, and communication efforts to address car-centric mindsets are identified as the policies with the highest transformative potential from those analysed; (2) carbon and road prices have an anticipatory intent and a low and medium transformative potential, whereas efforts to improve infrastructure for public and active transport modes while reducing travel costs have a transformative intent and a medium transformative potential; and (3) incentives for private electric vehicles do not weaken or help to shift away from, and rather reinforce, the system dynamics underlying induced car demand and urban sprawl; as such, they have an anticipatory intent and a low potential to transform the system (figure 14; appendix pp 27–29).

The policy concludes that shifting the focus of the electrification strategy away from replacing the internal combustion engines of private cars with electric motors is key to transformative change. Electric vehicle subsidies need to be reassessed to prioritise electrifying frequently used vehicles and more sustainable modes (eg, on-demand shared services, micro-mobility, bicycles, and e-bicycles with appropriate measures to enhance safety for users and pedestrians). Subsidies for private car use should be made the exception, such as in the case of very isolated communities for which the use of other modes is not possible.

Discussion

The Pathfinder umbrella review confirmed the large potential benefits for greenhouse gas emissions and health of well designed and implemented actions, particularly in the energy, AFOLU, and transport sectors, but also showed wide variability of impacts depending on the type of action and context. In general, modelled actions with a defined mechanism of action had much smaller estimated effects on both emissions and health than those reliant on an assumption of large-scale behaviour change without explaining how this would be achieved. However, at present, most implemented actions are not fully capitalising on the potential health benefits that could be theoretically achieved, nor are they demonstrating that pledges to cut emissions are being turned into action at the scale and rate needed to reach net zero and avoid climate change. An increase in the number and diversity of examples of implemented action is needed to show how to address the challenges of measuring climate, health, and other benefits of implementing climate actions in diverse settings. It is currently unclear whether and, if so, how the scale of co-benefits suggested by modelling studies could be achieved. This emphasises the need for more applied research focused on mechanisms to achieve large-scale changes.

Data and research gaps

Many systematic reviews were excluded from our umbrella review because of an absence of either quantified health or greenhouse gas mitigation outcomes (see panel 4 for a discussion on data limitations). This absence suggests that a large body of research on health and climate change mitigation effects of potentially relevant actions has been synthesised in disciplinary silos and that there could be substantial potential for their integration. The more distant the processes through which actions trigger health and climate change mitigation effects or the less certain the evidence base is on these effects, the less likely they were to be captured in our results. For instance, we found no reviews of studies on health co-benefits of mitigation actions in the oceans.

Other significant research gaps include a general scarcity of evidence on the effects of actions in LMICs and on inequities; on circular economy approaches; and on nature-based solutions. Mental health outcomes were largely absent from the published literature and should be included in future evaluations. Evaluations of implemented real-world actions are deficient in several ways. First, almost all the examples included here provided measures of effect but offer little insight into the processes and factors that contribute to success or failure of implementation, unintended consequences and trade-offs, or an assessment of potential scale-up or generalisability. Second, many studies either provide estimates on mitigation or health benefits, but not both and were therefore excluded from our analysis. The research framework for the Pathfinder review of implemented action was limited to those cases where both mitigation of greenhouse gases and health exposures or outcomes were measured in tandem, but the findings were echoed in the recent Global Stocktake report, which has highlighted the large gap in implementation between stated targets and currently enacted policies and actions.[210]

Robust data on the effects of climate mitigation actions are needed to assess the true benefits to the environment and human health and to minimise and avoid potential trade-offs. Moreover, the health co-benefits from different sectoral actions cannot simply be added together because they often affect the risks of the same non-communicable diseases, including cardiovascular disease and diabetes. Adjustment for competing risks is needed in modelling studies that aim to project the impacts of climate actions that affect different sectors and pathways.

Future work should also aim to integrate estimates of health co-benefits over both short and long timescales, and for both the reduction of the dangerous impacts of climate change and those co-benefits for which there might be longer time lags in realising the full benefit to health (eg, reductions in lung cancer incidence from air pollution). More generally, the scarcity of consistent approaches to estimating health co-benefits reinforces the need to follow guidance on the design and reporting of health co-benefits assessments.[211] In view of the weak evidence base on LMICs, strengthening research capacity will be essential and this should be accompanied by efforts to increase the demand for research evidence from policy makers and implementers.

Synergies and trade-offs of climate mitigation actions can depend on the means of implementation, timing, and stringency, as well as the political and developmental context.[15] To capitalise on synergies and minimise trade-offs, it is essential to include vulnerable and marginalised peoples in the planning and implementation process. A systematic assessment of trade-offs between climate and health, paired with thoughtful and evidence-based design and implementation of interventions, can minimise any potential negative impacts. Furthermore, increased knowledge and understanding of trade-offs can increase the cost-effectiveness and efficiency of climate action.[212]

There were major gaps in assessing NBS impacts on health and greenhouse gas emissions. Natural ecosystems potentially generate multiple physical and mental health benefits, many of which were not captured by our review of studies. The gap in the literature is partly related to the artificial divide between adaptation and mitigation. Our review shows that studies documenting mitigation actions rarely reported the associated adaptation impact, and the reverse is probably true as well. The gaps in evidence could be attributed to methodological challenges; assessing the health impacts of changes in ecosystems requires in-depth assessments in the biophysical

Panel 4: Limitations of existing literature on co-impacts between climate change mitigation and health

- Interventions assessed in reviews are highly heterogeneous and cover vastly different scales.
- The interventions and their context are only briefly described, which limits analysis, assessment of applicability, and replication.
- Studies evaluating implemented actions frequently fail to indicate the baseline emission or exposure and might not include all greenhouse gases, which prevents accurate quantification.
- Even when studies provide a baseline measure of greenhouse gas emissions or health exposure, it is often unclear whether the intervention assessed could reduce emissions sector-wide, and across regions and income levels.
- The health impacts of some greenhouse gases, such as nitrous oxide, have been relatively neglected in research,[43] and further studies are required to improve dose–response relationships.
- Only a few studies assess synergies and trade-offs, either within a sector or between sectors, and on other environmental outcomes.
- There are major gaps in data (both modelled and implemented) from low-income and middle-income contexts, such as Africa, and these should be prioritised in future research to foster understanding of the health benefits of low-carbon development.
- Processes by which greenhouse gas emissions and health outcomes are impacted by interventions are currently diversely reported, if at all. Consequently, the contributions of different pathways remain uncertain. Mental health outcomes are rarely reported.
- Co-benefit reviews are from diverse disciplines, often without explicit consideration of health outcomes. Greater collaboration between public health and sectoral researchers is imperative.
- The potential to integrate adaptation and mitigation is rarely considered, contributing to policy fragmentation and increasing the potential for trade-offs.
- Disaggregated data on equity and a just transition (eg, gender, education, disability, and income status) are largely lacking from both modelled and implemented data. This omission hampers efforts to assess the equity implications of climate mitigation efforts and ensure potential health co-benefits are fully realised.[28]

structure of the given ecosystem, shifts in ecosystems functions and services, and associated changes in human wellbeing.[213] Many of the reviewed NBS studies could have gone further in linking changes in ecosystem services to human health. For example, studies of air quality improvements from urban trees could have assessed the impact on respiratory outcomes. The studies estimating the energy savings from cooling and shading from trees could have examined the impact on heat-related deaths.[214] Equally, studies on agroforestry could quantify the impact on dietary diversity, which is a proxy for nutrient adequacy of individual and household dietary intake.[215] At least 36% of intact forest landscapes are within Indigenous peoples' lands and have lower forest loss rates than on other lands, but Indigenous peoples' health and perspectives are often neglected.[216]

There is a need for improved understanding of the pathways and mechanisms by which carbon pricing policies contribute to health and wellbeing, and how these depend on context, policy design, and policy interactions. In parallel, we also need to better understand how health impact assessments can better inform policy adoption, design, and implementation. There is a growing consensus that these policies cannot, by themselves, generate the necessary societal changes to mitigate climate change, but they can be a component of a broader transformative strategy. This is because carbon pricing can affect incentives throughout societies and economic systems while also potentially raising revenues or redistributing wealth.[217]

Moving from modelled evidence to implemented actions

Although modelled estimates show the potential for major health co-benefits from mitigation actions, particularly in the energy, AFOLU, and transport sectors, the dearth of implementation case studies, together with their generally limited scope and scale, shows the magnitude of the challenge to achieve the Paris Climate Agreement targets and capitalise on the potential. Collectively, human activities were responsible for the emissions of about 56 gigatonnes of CO_2eq each year during 2010–19, about 9 gigatonnes of CO_2eq per year higher than in the previous decade.[15] This is the largest recorded increase in average decadal emissions. Limiting global temperature increase to below 1·5°C with no or little overshoot requires ambitious greenhouse gas reductions of 34–60% by 2030 and 73–98% by 2050, relative to 2019 levels.[15]

The implemented actions documented in our case studies make fairly small contributions to the necessary emission reductions, with the largest of these amounting to 147 megatonnes between 2005 and 2016 (see Energy sector case study). This result might be partly because many mitigation efforts do not measure health exposures or outcomes. Robust measurement and reporting can help guard against false claims, feed into cost–benefit analyses,[218] and allow implementing actors to identify and respond to trade-offs, and adjust accordingly if actions do not achieve the results predicted from modelled projections. For example, much of the evidence from the umbrella review focuses on dietary change, and this was also identified as one of the areas where the biggest co-benefits for health could be achieved. However, practical dietary interventions were notable by their absence in the case studies. For example, a school-based intervention in Sweden showed that more sustainable meals could be achieved with no apparent reduction in palatability, but this study stopped short of identifying any tangible health benefits, as implementation of this intervention occurred over a short period of time.[219] A recent study has shown the potential air pollution co-benefits of dietary change from reductions in particulate matter and tropospheric O_3 from reduced animal product consumption and increased consumption of plant-based flexitarian, vegetarian, and vegan diets. On a global scale, dietary change could lead to estimated reductions in premature mortality of 108 000–236 000 from reduced air pollution. Enhanced labour productivity from cleaner air increased economic output by about US$1·3 trillion (with a range of $0·5–3·0 trillion).[220] Therefore, further evaluations of interventions to achieve sustained dietary changes in diverse populations should be a priority.

In the transport sector, some small-scale (ie, single-city) interventions were found for which health benefits had been estimated, and it will be important to demonstrate that these actions can be scaled up. Evidence from the umbrella review on urban transport suggests that the potential for mitigation and health benefits can best be achieved through a combination of increased provision of public transport, active travel, and electric vehicles, with attention given to reducing road danger for pedestrians and cyclists. Recent estimates suggest a global reduction of 686 million tonnes of CO_2 annually is possible if a Dutch cycling pattern was followed worldwide, with a daily cycling distance of 2·6 km.[221] This is about 20% of the greenhouse gas emissions from the global passenger car fleet in 2015 and could also prevent about 620 000 premature deaths. However, realising such benefits would be challenging because it depends on a range of pro-cycling policies, including the provision of infrastructure and policies to discourage car use. The Model Communities Programme in New Zealand showed that active travel policies must be combined with actions to increase public transport and reduce the use of private cars in urban centres to achieve health and climate benefits. Achieving the potential magnitude of health benefits of active travel depends on the participation of middle-aged and older people, for whom the benefits of physical activity are large. There is moderate evidence that use of e-bicycles might improve cardiorespiratory fitness in the physically inactive.[222]

Case studies of examples of actions in the energy sector show how tangible benefits for health and the climate can be realised at a national scale from the application of renewable energy standards in the USA.[83–85] More rapid action can be facilitated by using multiple reinforcing approaches, for example by combining regulation, subsidy removal, and carbon pricing. The size of the health co-benefits of clean energy depends on the type of fossil fuel energy displaced and local pollution control measures, with larger benefits in those countries with high levels of fossil fuel-related air pollution.[40] Actions to promote clean renewable energy do not require major changes in behaviour and might therefore be easier to implement than other climate actions once price differences and energy intermittency issues are addressed.

Between 71% and 76% of global energy-related carbon emissions originate from activities in cities.[223] Population growth is largely in cities and there is an opportunity to design the cities of the future, particularly in low-income countries where population growth is greatest. Currently, more than 40 cities are operating on 100% renewable electricity and a further 100 cities have reported at least 70% of their electricity coming from renewable sources.[224] African cities are now transitioning to the use of renewable energy sources, with 184 cities using solar photovoltaics, 189 generating electricity from wind, and 275 cities using hydropower.[224] China's national government has initiated many pilot projects to promote city-level, low-carbon development. From 2010 to 2015, city-level actions to move away from fossil fuels towards clean energy, combined with energy efficiency measures, have reduced carbon intensity by 45·8%.[22,225] However, carbon intensity cannot be used as an overall measure of greenhouse gas emissions because total emissions can increase despite reducing carbon intensity if economic activity is increasing rapidly. In China, 41% of cities experienced rising $PM_{2\cdot5}$ concentrations despite decreasing their carbon intensity,[225] and national greenhouse gas emissions in China rose by more than 3·4% to 14·3 gigatonnes of CO_2eq in 2021. Despite the range of climate mitigation actions being undertaken in cities, there are few examples of actions that evaluate changes in both greenhouse gas and health-related indicators, suggesting missed opportunities for capitalising on health co-benefits.[21] Cities need to be planned and managed to minimise pressure on existing open land, infrastructure, and services, avoiding crowding on the one hand and unsustainable sprawl on the other. Integration of clean energy, improved housing, improved water and sanitation, public transport and active travel, accessible health services and education, and adequate greenspace are essential to achieve climate-resilient net-zero development.[226]

Few studies were identified that provided evidence of implemented real-world actions that measure both greenhouse gas mitigation and health effects. In addition, most identified evaluations reported solely on direct impacts and offer little insight into the processes and factors that determine success or failure of any given action or aid assessment on scaling action to new settings. Therefore, there is a need for more rigorous evaluations of interventions (and syntheses of such evaluations) that go beyond only measuring impact, to those that also uncover the mechanisms of action and assess the implementation processes, contextual barriers, and enablers of these actions.

The diversity of timescales and metrics used across a range of co-benefits studies reinforces the need to follow guidance to improve the quality and usability of research.[211] Adaptation of current guidelines for the evaluation of complex interventions, natural experiments, and process evaluations to encompass measures of greenhouse gas emissions would provide helpful benchmarks for rigorous evaluation of health and climate effects of mitigation actions.[227–229] Evaluations that assess how to achieve change should also inform how scale-up can be achieved. Continuous updating of evidence on climate mitigation using living review methods pioneered during the COVID-19 pandemic would bring evidence faster to the attention of the research, practitioner, and policy communities.[230,231]

An approach that puts planetary health at the centre of policy making, from design to implementation and evaluation, will be needed to accelerate transformation towards a net-zero economy. This approach implies going beyond health as a co-benefit, and beyond the design of ex-post compensatory measures to mitigate inequalities. Putting health at the centre of climate mitigation efforts, alongside broader notions of justice and wellbeing, can help reframe transformation efforts towards more intrinsically equitable and sustainable notions of needs and wellbeing and away from exclusively monetary measures of success. Existing frameworks that can help inform this reframing include the World Report on Social Determinants of Health Equity,[62] Sustainable Development Goals,[232] doughnut economics,[233] and the OECD wellbeing framework,[61] as well as the Earth for All report.[234] The last of these is a report to the Club of Rome on the 50th anniversary of the ground-breaking Limits to Growth report that issued a clarion call of warning about the hazards of business-as-usual policies in the long term, with some of the scenarios they examined leading to civilisational collapse.[235,236] The Earth for All analysis proposes five essential turnarounds: ending poverty, addressing gross inequality, empowering women, making food systems healthy for people and ecosystems, and transitioning to clean energy. These actions can all improve health and accelerate progress to net-zero emissions.

For more on **climate policies and results in China** see https://climateactiontracker.org/countries/china

There are opportunities to embed health into the Paris Climate Agreement, for example by integrating health into the NDCs that each signatory nation submits. A 2023 WHO analysis of the contribution of health to NDCs has shown that although over 90% mention health, less than one third (30%) identify health co-benefits from national mitigation action and only one in ten (10%) quantify or monitor those co-benefits.[237] There are also unrealised opportunities to embed health into long-term low greenhouse gas emission development strategies (LT-LEDS) that provide a horizon for the short-term aspirations of the NDCs. The Global Stocktake is the process by which progress towards climate targets can be assessed, and the integration of health metrics into monitoring of progress on mitigation (and adaptation) would ensure that negotiations considered the impacts of climate change on health and the potential for co-benefits from increased action.

For more on the **Global Stocktake** see https://unfccc.int/topics/global-stocktake

Building the evidence base for action

An interactive Pathfinder Climate and Health Evidence Bank has been developed, sharing the outputs of the umbrella review and the case studies of implemented mitigation actions. Evidence collected and synthesised through the Pathfinder Initiative should be used to create a machine learning-assisted living systematic map of the evidence on climate and health with a particular focus on mitigation actions, incorporating both primary studies and evidence syntheses. This evidence base will provide a key resource for the scientific community as well as users of evidence by improving accessibility to climate mitigation and health research that is currently highly dispersed across very different communities. The living map will form the basis for additional targeted systematic reviews, providing a continually updated source of studies on relevant topics and helping to identify gaps in the evidence base. Existing evaluation guidelines (complex interventions, natural experiments, and process evaluations) will be adapted to encompass measurement of climate mitigation actions during the next phase of the Pathfinder Initiative. Currently available tools and resources for estimating climate change mitigation impacts on greenhouse gas emissions and health will also be refined to ensure wide applicability and the use of best available evidence.

Leveraging the health co-benefits of mitigation action to promote change

The journey towards net zero requires transformation of all major sectoral systems, radically changing the ways business and the public sector operate and interact with the natural environment to steer societies towards a healthy, equitable, and sustainable net-zero carbon development pathway. This transformation will require reducing the material demand for products and services responsible for large greenhouse gas emissions in countries with high per-capita emissions, as well as exploiting technological solutions that support efficient and equitable use of energy and resources. Increasingly, the aim should be to fund and implement actions for net-zero resilience that enable societies to withstand climate shocks while functioning at much lower environmental footprints than those of industrialised countries and emerging economies.[232]

Engagement from all sectors in the societal and behavioural changes required to reach net zero is essential to climate change mitigation.[238] Although most people globally are concerned about climate change, there remain barriers to behaviour change and to the support for transformative policies.[209] Behaviour change strategies should be considered as part of wider efforts to address systemic and structural barriers to change, including inequities in access to clean energy, healthy diets, and safe, affordable public transport and active travel. Examples include increasing the proportion of plant-based meal choices in UK cafeterias, leading to increased selection.[239]

The OECD report on redesigning Ireland's transport system for net-zero emissions is an example of a systemic approach that challenges engrained mindsets that equate high and growing mobility with wellbeing and redefines the goal of the transport system as the provision of sustainable accessibility to services and resources. It aims to prioritise the scale-up of policies with high potential to transform the current car-dependent system and to revise measurement frameworks and metrics of success (see section on transformative change for further discussion).[209]

Health co-benefit framings appear to be at least as effective as climate benefit framings to promote mitigation behaviours, including dietary and travel habit change. For dietary change, some studies find health messages are more effective than other framings in increasing intentions to reduce meat consumption,[240] whereas others find they are no more effective than environmental messages,[241] suggesting the need to understand better how to tailor messages to different populations. Other research shows that personal health and environmental benefit framings are equally effective in promoting plant-based diets and reducing red or processed meat consumption, although the combination of these framings produced more durable behavioural effects,[242,243] at least for more sustainability-conscious consumers.[244] For low-carbon travel, research similarly shows that health benefit messaging to promote active travel is more persuasive than other arguments (eg, convenience or environment) for walking, particularly when advocated by an expert source.[245] Health arguments are less persuasive to young people than to older people,[245] because young people are more influenced by cost and environmental factors in choosing active modes.[246]

Recommendations

Through this work, we have identified actions across three broad headings and for a variety of stakeholders to accelerate progress towards healthy societies with net-zero greenhouse gas emissions in compliance with the Paris Climate Agreement.

Leadership to support ambitious, collective, and transformative action on climate and health

There is an urgent need for committed political leadership and a step-change in evidence-informed action on climate and health. To achieve this, a coalition of high-ambition national and subnational governments, organisations, and other entities across a range of settings should commit to leading by example and sharing learning from implementation of climate change mitigation policies (panel 5).

Climate funders and policy actors should support the co-design of actions and implement them with the active engagement of relevant stakeholders, including affected populations, using systems approaches designed to increase equity and address potential trade-offs.

Integrating health into all climate policies

Parties to the Paris Climate Agreement should support the integration of health into climate policies, including by ensuring that future NDCs and LT-LEDS include the quantification of the health co-benefits of climate action, monitored and reported through the Global Stocktake process. This requires the development of an evidence infrastructure for the Global Stocktake, including data on health and equity co-benefits of climate action and wider efforts to strengthen capacity on climate and health linkages. The health effects of mitigation of short-lived climate pollutants (eg, black carbon and CH_4) as well as of CO_2 should be included in integrated policies.

Making a compelling case for change

International and domestic funders of climate change mitigation should support implementing agencies and governments to use standard approaches to assess the health impacts of these actions. This collaboration will facilitate the measurement, tracking, and reporting of co-benefits and trade-offs strengthening human development and the case for change.

Health professionals and policy makers should clearly communicate the potential health and economic co-benefits that transitioning to a more equitable net-zero society can bring across all sectors, in addition to facilitating the rapid decarbonisation of the health-care sector (panel 6).

Better evidence for decision making

To enable faster and easier learning across studies and contexts. Researchers and research funders should support: (1) real-world, at-scale intervention evaluations and the data collection systems required for these, including on mental health outcomes; (2) the development and use of well validated decision support tools to accelerate the integration of health into climate mitigation policies; (3) harmonisation of both modelling and evaluative research methods across health co-impact pathways; (4) efforts to strengthen research capacity where it is most needed, particularly in collaboration with LMIC researchers and Indigenous communities; and (5) living syntheses of research evidence that can both help to communicate important emerging evidence and highlight crucial evidence gaps or questions.

> ***Panel 5*: Principles of the proposed coalition**
>
> 1 Implementing rapid reductions in greenhouse gas emissions consistent with the Paris Climate Agreement targets through evidence-based actions that aim to improve health and health equity.
> 2 The use of key principles from systems thinking and implementation science in the design and delivery of actions, including the co-design of actions to optimise benefits to health and wellbeing and minimise harms, and a thorough assessment of potential trade-offs.
> 3 An ongoing assessment of the success or failure of actions through regular measurement and reporting on progress using robust evaluation methods, including following the Paris Agreement rulebook for emissions and standard approaches to estimating changes in health-related exposures, determinants, or outcomes, or a combination of the three, as well as the costs of action and wider social impacts (eg, employment or poverty).
> 4 Supporting mutual learning—eg, agreement to share lessons, including barriers and facilitators of success, and resources, such as training materials and courses, technical manuals, decision support aids, and the like. Communicating lessons learnt to their constituents and members, combating misinformation where necessary.

Targeted action on urgent data gaps

To address urgent data gaps and inform policy formation, researchers and research funders should target research and synthesis efforts on links with a range of relevant disciplines, sectors, and data gaps including: (1) integration of and lessons from research on health policy and social change to understand how social tipping points in mitigation and health can be achieved; (2) research on the commercial determinants of health and the underlying societal drivers that must be addressed to promote demand reduction; (3) the role of NBS and natural climate solutions in delivering equitable mitigation and adaptation benefits, while promoting human health and wellbeing; (4) actions to strengthen capacity to collect and analyse data within currently low-emitting countries to enable a just and equitable transition to a low-emission future; and (5) the health co-benefits and greenhouse gas reductions from actions to mitigate short-lived climate pollutants (eg, CH_4 and black carbon).

Next steps

Developing a coalition on climate action for health

We urge the formation of a coalition of like-minded organisations that recognise that more action is needed if we are to reach net-zero emissions and limit hazardous levels of global heating. We invite support for the

Panel 6: Glossary

Bioeconomy
An economy where the basic building blocks for materials, chemicals, and energy are derived from renewable biological resources.

Decarbonisation
Technically just carbon reduction but often used to mean reductions of all greenhouse gases; here, we use it in its widest context.

Efficiency
The continuous, short-term, marginal technological improvements that allow doing more with less in relative terms without considering the planetary boundaries.

Global Stocktake
The Global Stocktake was established under Article 14 of the Paris Agreement; it is defined as a process for countries and stakeholders to see where they are collectively making progress towards meeting the goals of the Paris Climate Agreement—and where they are not.

Incremental change
"The situation in which systems' goals and dynamics remain unchanged, and policies' efforts focus on changing the properties of the systems' parts, as to 'fix' or minimise the negative impacts produced by the system".[201]

For more on **Radical Listening** see https://radicallistening.org/

Long-term low greenhouse gas emission strategies
Long-term climate strategies prepared by signatory countries that carry emission reduction strategies through to 2050 and submitted to the Secretariat of the UN Framework Convention on Climate Change.

Nationally determined contributions
A term used under the United Nations Framework Convention on Climate Change (UNFCCC), whereby a country that has joined the Paris Agreement outlines its plans for reducing its emissions.[247]

Nature-based solutions
"Actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human wellbeing and biodiversity benefits".[68]

Net zero
Net-zero emissions are achieved when anthropogenic emissions of greenhouse gases to the atmosphere are balanced by anthropogenic removals over a specified period. Where multiple greenhouse gases are involved, the quantification of net-zero emissions depends on the climate metric chosen to compare emissions of different gases (eg, global warming potential, global temperature change potential, and others, as well as the chosen time horizon).[247]

Paris Climate Agreement
Under the UNFCCC, the Paris Climate Agreement was adopted in December, 2015, in Paris, France, at the 21st session of the Conference of the Parties to the UNFCCC. The agreement, adopted by 196 parties to the UNFCCC, entered into force on Nov 4, 2016 and, as of May, 2018, had 195 signatories and was ratified by 177 parties. One of the goals of the Paris Agreement is "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1·5°C above pre-industrial levels".[247]

Radical Listening
A process defined by Health in Harmony as a "way of witnessing and listening to a group as they enter into authentic conversation with one another. It recognizes and honors the fact that they are the experts in their problems. And their solutions."

Spillovers
"International spillover effects are said to occur when one country's actions generate benefits or impose costs on another country that are not reflected in market prices, and therefore are not 'internalized' by the actions of consumers and producers."[248]

Transformative change
"The situation in which—by changing its goals and dynamics—the system achieves different results than the system of the past".

foundation of a coalition of willing signatories of those taking action to mitigate greenhouse gases, including but not limited to cities, nations, non-governmental organisations, businesses and their representative bodies, and funding agencies, to sign up to a set of core principles to accelerate ambition and foster mutual learning. The coalition aims to be inclusive and realise that not all signatories will be able to fulfil all commitments from the outset but that they are willing to co-develop a roadmap to fulfil the commitments and engage in dialogue and action to help develop the tools, metrics, and indicators alongside experts in climate and health research, policy, and communications. Membership implies a willingness to monitor and share data on greenhouse gas emissions, health exposures, and outcomes over time to prospectively measure progress towards climate and health goals.

The coalition will comprise: (1) research partners—ie, academic collaborators to support further synthesis and application of evidence to local contexts; (2) enabling partners—ie, networks of organisations working on or funding projects on climate mitigation and health, including partners from Pathfinder phase 1 (OECD, SDSN, CDP, and C40 Cities), WHO, and major climate funders; and (3) implementing partners—ie, organisations that are already implementing or planning greenhouse gas mitigation actions that are likely to have significant health co-benefits, including those identified through the umbrella review and case studies.

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Implementing partners will use tailored tools, guidelines, and briefs to identify relevant metrics, data, and indicators for at least one climate mitigation intervention that has health co-benefits. They will also measure and monitor progress on mitigation actions, including greenhouse gas emission reductions, health-relevant exposures (eg, air pollution), and policy-relevant outcomes, with a particular focus on equity.

Strengthening capacity on monitoring and evaluation

The coalition should support the implementation of high-ambition climate change mitigation initiatives by strengthening the capacity of partner organisations, including providing expert technical support and enabling rapid sharing of evidence within and beyond the coalition. This should draw on the WHO seven principles for (research) capacity development[249] and will include: (1) initial diagnostic and demand assessment, involving a light-touch organisational self-assessment to assess specific areas where current capacity—either in-house or contracted in—is limiting the pace or ambition of decarbonisation action; these assessments will be used to develop a prioritised capacity strengthening programme; (2) establishment of a community of practice across the coalition, using a combination of online and in-person learning exchanges; and (3) determining critical factors for scaling successful greenhouse gas mitigation initiatives; these factors will include developing capacity-building packages that can be effectively adapted and transferred to other settings, including methods of co-designing evaluation metrics, encompassing delivery of webinars, workshops, and open-access educational and training materials.

Pathfinder Climate and Health Evidence Bank

An interactive Pathfinder Climate and Health Evidence Bank has been developed to share the outputs of the umbrella review and the case studies of implemented mitigation actions. Evidence collected and synthesised through the Pathfinder Initiative can be used to create a machine learning-assisted living systematic map of the evidence on climate and health with a particular focus on mitigation actions, incorporating both primary studies and evidence syntheses. This will provide a critical resource for the scientific community as well as users of evidence by improving accessibility to climate mitigation and health research that is currently highly dispersed across very different communities. The living map will form the basis for additional targeted systematic reviews, providing a continually updated source of studies on relevant topics and helping to identify gaps in the evidence base. Existing evaluation guidelines (complex interventions, natural experiments, and process evaluations) will be adapted to encompass measurement of climate mitigation actions. Currently available tools and resources for estimating climate change mitigation impacts on greenhouse gas emissions and health will be refined to ensure wide applicability and the use of best available evidence.

Conclusions

The Pathfinder Initiative has identified a range of potential greenhouse gas mitigation win-win actions in different sectors that can benefit both health and the climate, particularly when implemented in ways that can improve equity and minimise trade-offs. More evidence of effective implementation strategies is needed but this does not imply waiting for evidence before acting. Continuously updated living reviews can make evidence available to researchers, policy makers, and implementers in a timely fashion. Evaluation of the effects of mitigation actions on health, equity, and greenhouse gas emissions must be undertaken in real time, using standardised approaches informed by guidelines so that outcomes are comparable across sectors and locations. This evaluation will be essential to combat disinformation and so-called greenwashing that impede progress and prevent objective assessment of the impacts of climate action. Transformative approaches that aim to safeguard health while achieving net-zero greenhouse gas emissions within planetary boundaries must be developed and implemented at scale through equitable collaboration and shared learning.

Contributors

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Declaration of interests

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Supplementary appendix

This appendix formed part of the original submission and has been peer reviewed. We post it as supplied by the authors.

Supplement to: Whitmee S, Green R, Belesova K, et al. Pathways to a healthy net-zero future: report of the *Lancet* Pathfinder Commission. *Lancet* 2023; published online Nov 20. https://doi.org/10.1016/S0140-6736(23)02466-2.

Pathways to a healthy net-zero future: report of the Lancet Pathfinder Commission

Web Appendix

A1: Conceptual framework: Theoretical research framework for mapping evidence on climate change mitigation action and health

Introduction

There are various classifications, categorisations and frameworks used to map climate change mitigation actions and their health impacts[1–4] These are, however, not designed for research focussing on implementation, including political economy aspects and on *how* actions work, and for whom. For example, it is often unclear what constitutes an action or intervention and their main components; and inequalities in outcomes are often neglected. The lack of a comprehensive framework hampers mutual learning and some types of research including studies of contextual factors that can influence the feasibility and scale of implementation. As part of the Pathfinder Initiative, a framework was developed that was designed to capture evidence from across all sectors with a focus on implementation of climate change mitigation actions and its impacts on health. The development and final framework described here was later superseded by two published research protocols for the umbrella review[5] and the review of implemented actions.[6]

Aims

To create a framework and classification for mapping and characterising actions for climate change mitigation and h their health outcomes. The framework is intended to be used for reporting and mapping evidence, facilitating both quantitative and qualitative analysis, comparison and mutual learning of what works, how and for whom.

Methods

Development of the research framework was based on a review of existing classifications and frameworks for climate change mitigation actions and health outcomes used by institutions involved in designing or influencing climate policy at an international level including IPCC[4], Drawdown[7], OECD[8] and WHO[9]. The framework also draws on specific resources for classification of behavioural solutions[10], ocean-based solutions[11], the health and education sectors[12,13] and urban nature-based solutions.[14] Further development of the framework involved discussion and consultation from the network of project partners and participants in the Lancet Pathfinder Commission and broader Pathfinder Initiative The resources used to inform the framework are shown in Table A1.1 and the final framework is presented in Figure A1.

Table A1.1 Key institutional and academic typologies, classifications and frameworks reviewed to create Pathfinder conceptual framework.

Institutional typologies, classifications or frameworks	**Coverage**	**Reference**
IPCC Classification and evidence synthesis	Multiple sectors/ Whole system	(IPCC, 2014a) Technical summary, tables TS.3 to TS.8
IPCC Health impacts mapping	Multiple sectors/ Whole system	(IPCC, 2014b) Impacts, Adaptation and Vulnerability, chapter 11, Human Health

EU Commission Behaviour change interventions classification	Behaviour change	(Faber et al., 2012)
Drawdown Solutions mitigation strategies	Multiple sectors/Whole system	(Drawdown, 2020)
Ocean Panel/WRI ocean solutions	Ocean solutions	(Hoegh-Guldberg et al., 2019)
OECD Wellbeing framework	Multiple sectors/Whole system	(OECD, 2021)
WHO social determinants of health framework	Social determinants of health	(WHO Commission on Social Determinants of Health & World Health Organization, 2008)
UNESCO education for climate change action	Education	(UNESCO, 2020)
Family planning health impacts	Family planning	(Guillebaud, 2016)
UK NHS and department of health Green Plan for sustainable healthcare	Healthcare	(NHS England SDU, 2009), (Department of Health, 2020)
Good practice menu	Multiple sectors/Whole system	(Climate Policy Database, n.a.)
Academic frameworks and typologies		
THRIVES framework	Urban design and planning	(Pineo, 2020)
CRAFT tool/ framework	Urban environmental policies	(Symonds et al., 2020)
Reporting on climate change mitigation and health	Not sector-specific	(Hess et al., 2020)

Context

Given the focus of this framework, we consider context to include drivers of climate change action and structural determinants of health based on the WHO Commission on Social Determinants of Health (WHO CSDH), expanded to include environmental determinants.[15]

Context includes:

a) Environmental quality and fragility (typology to be developed or adapted)
b) Other structural factors shaping health as well as climate action.
    - Economic structure (e.g. Sectoral structure, including interaction with natural environment)
    - Labour market
    - Educational system,
    - Political institutions
    - Cultural and societal values – including interactions with the natural environment.
c) Social inequities: income, education, occupation, social class, gender, race/ethnicity. This includes not only differences in income and wealth but also rights, resource access and discrimination.

We are interested to understand how the context generates:

- Barriers and opportunities
- Context-intervention interactions

Actors
This category reflects who is influencing, designing, implementing the action and strategy. For the analysis within the umbrella review it was initially examined but subsequently removed as it was not judged useful for evidence mapping.

Climate change mitigation actions
This category reflects what actions are being modelled or undertaken that are relevant to greenhouse gas (GHG) mitigation and health. An initial summary classification of mitigation actions was created based on a list of specific climate change mitigation actions (Table A1.2). This bottom-up approach to defining categories allows for added flexibility and re-definition, for example, in cases where specific solutions within a category have substantially different health impacts, or where additional detail might be wanted. Mitigation strategies were also classified according to the sector they target and systemic actions that adopt a system-wide or sectoral approach are classified separately. Examples include a cross-sectoral carbon tax, or a package of interventions that complement each other across housing, transport and green spaces.

Table A1.1. Summary classification of mitigation actions.

Coverage	**Mitigation action categories*** (*Some actions may have potential negative impacts on health)
System-wide and cross-sectoral interventions	
Energy	Renewable energy technologies
	Improved energy storage, use and distribution
	Carbon capture and storage
	Increased energy efficiency of buildings and appliances
	Clean cookstoves
	Replace fossil fuel energy by nuclear
Transport	Alternatives to private cars including public transport and active travel
	Reduced demand for travel
	Energy-efficient transportation
	Electric/Hydrogen powered transportation
	Biofuel, Diesel, (CNG)
AFOLU-Oceans	"Sustainable" intensification of agriculture/aquaculture/fisheries
	Agroecology
	Nature-based solutions/non-urban (e.g. Restoration and conservation of forests and other ecosystems, peatland rewetting, tree plantation in degraded land, protecting indigenous peoples' forest tenure)
	Low-GHG emission diets-including plant-rich diets (within recommended dietary guidelines), dietary shift towards low-GHG emission ocean-based products,
	Reduce household food waste
	Use of e-commerce food delivery
Industry	Switch to materials less intensive in GHG emissions than current materials
	Improved resource management, including recycling
	Reuse and manage industrial process emissions incl. carbon capture and storage

	Reduce consumer waste
	Reduce product demand
Human Settlements	Infrastructure changes enabling behaviour change
	Nature-based solutions for urban areas
Healthcare and Education	Promote voluntary family planning
	Education for climate empowerment
	Women's access to education
	Sustainable healthcare

Strategies for implementing actions
This category reflects how climate change mitigation actions are implemented. The adoption of mitigation actions requires strategies implemented at a collective or institutional level, which lead to context-specific outcomes on the environment, society and health, for example, carbon tax and subsidy removal to encourage shift to renewables (Table A1.3). Other basic characteristics of the implemented strategy include its sector, scale or coverage (including system-wide and cross-sectoral interventions) and whether there are relevant interactions with other strategies (e.g. whether they should be considered as part of a "package"). The IPCC categorisation of mitigation policies has been chosen as a starting point for a categorisation of strategies. Strategies identified through other resources or case studies that do not fit in the narrower IPCC classification have been added at the end. These include more bottom-up strategies such as community-led initiatives and creation of social enterprises.

Table A1.2. Types of mitigation implementation strategy

(From IPCC)
Economic Instruments - Taxes
Economic Instruments - Tradable Allowances
Economic Instruments - Subsidies
Regulatory Approaches
Information Programmes
Direct Provision of Public Goods or
Services
Procurement (government, communities, NGOs, businesses)
Private sector voluntary actions
Additional – other sources (provisional)
Green bonds – Green investment instruments
Creation of social enterprises
Incentives through discounted access to public services
Community-level incentives
Bottom-up initiatives – community-led or consumer-led initiatives

Health impact pathways
Pathways are the mechanisms through which the actions and strategies described above, which we can jointly refer to as "implemented climate mitigation actions," affect human health. Health impact pathways result from implemented actions, directly or indirectly and may include unintended consequences (trade-offs or spill-over effects).[15] They can be initially hypothesised as resulting from the interaction between climate mitigation action, contextual structural factors and intermediate determinants of health, resulting in a specific pattern and magnitude of health outcomes. These are classified and completed based on the social determinants of health framework,[15] combined with the OECD Wellbeing framework.[8]

Impact pathways include effects through:

a) Environmental quality and fragility
b) Other structural determinants of health
c) Social inequities
d) Intermediate determinants of health
e) Health feedback loops (from health outcomes and health inequalities to stratification and social determinants of health)

*Intermediate determinants of health are included as outcomes, as in many cases it is possible to extrapolate health outcomes from them. In cases where they do not qualify as an outcome they can still be included as part of the hypothesized pathway.

Outcomes

This section refers to environmental, socioeconomic and health outcomes (socio-economic outcomes are of interest particularly as mediators of physical and psychological health). The resources summarised in Table A1.1 are used to inform an initial classification of outcomes and risk factors which were then further modified based on research findings. Specific health pathways, risk factors and outcomes can be mapped onto this:

a) Environmental Impacts
    - Mitigation effects
    - Implications for climate change adaptation (not within the scope of the study but identified as crucial trade-offs, synergies or constraining factors)
    - Other significant environmental impacts. These can include, for example, biodiversity loss or change, waste, water, air, and soil quality.
    - Basic environmental justice principles (e.g. "polluter pays")
b) Intermediate determinants of health (Combining WHO CSDH and OECD)
    - Material and environmental circumstances – Capabilities
        - Income and wealth/poverty
        - Work and Working Conditions
        - Housing
        - Nutrition Security
        - Environmental quality
        - Safety
    - Psychosocial Factors
        - Knowledge and skills
        - Work-life balance (time use)
        - Social connections
        - Civic engagement
    - Behaviours and Biological Factors (nutrition behaviours, physical activity, tobacco consumption and alcohol consumption)
c) Health inequities (income, education, occupation, social class, gender, race/ethnicity)
d) Average physical and mental health impacts and population affected.

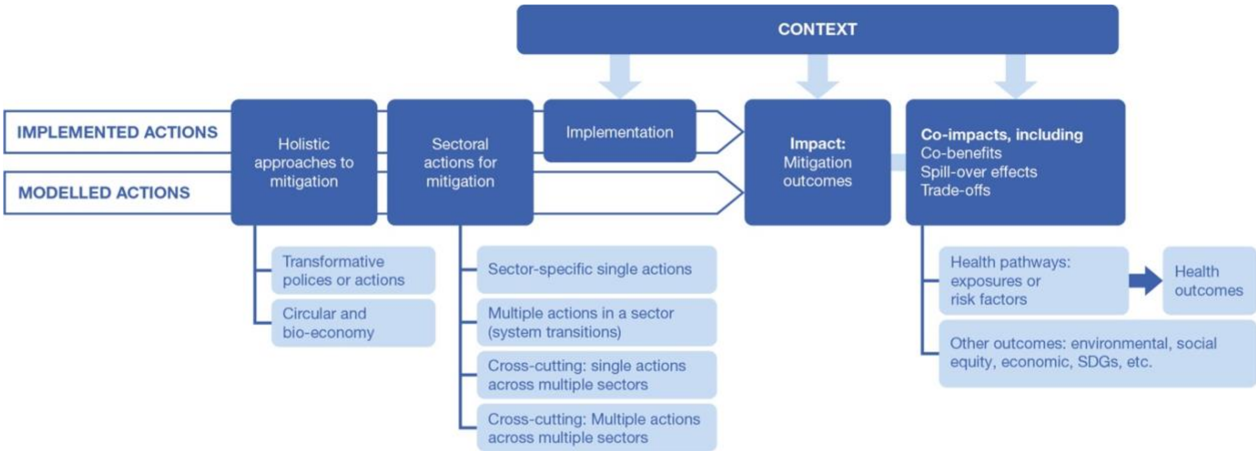

Figure A1. Greenhouse gas mitigation and health research framework. Climate change mitigation efforts can affect health through complex mechanisms, involving ancillary effects of mitigation (e.g., improvements in air quality), as well as other impacts resulting from the regulations, instruments and strategies employed (e.g. economic re-distribution and inclusion). The health impacts of mitigation actions and strategies are strongly mediated by social and environmental context, which can at the same time shape the space for climate policy. Analysis of impact mechanisms needs to consider the role of material, environmental, psychosocial, and behavioural determinants of health, as well as biological risk factors of the populations affected. Improved health and the reduction of social inequities are both central to the analysis, as well as fundamental to the success, and social legitimacy of climate change mitigation interventions.

A2: Search strategy for the identification of implemented mitigation actions that reduce emissions and benefit health.

Partnership with existing data holders and an open call for evidence
We engaged several major global collaborators to support data collection: The Organisation for Economic Co-operation and Development (OECD), C40 Cities, the Sustainable Development Solutions Network (SDSN), the Alliance for Health Policy and Systems Research (AHPSR), and the CDP. An open call for evidence was circulated through networks of the above collaborators and distributed to other international actors including major funders of climate action (e.g., the Green Climate Fund, Regional Development banks, bilateral donors, national and sub-national governments), UN agencies (including WHO and UNDP), the Climate Ambition Alliance, NGOs and the private sector (through organisations such as the World Business Council on Sustainable Development). The Pathfinder Initiative also incorporates the Lancet Pathfinder Commission, comprising members from all major global regions and many sectors involved with climate mitigation, that provides scientific guidance and oversight, and Commissioner networks were used to further circulate the call. A Comment was published in The Lancet outlining the Pathfinder Commission and its call for evidence to encourage submissions from readership of The Lancet,[16] and social media was used to further disseminate the call including through LinkedIn and X (formerly Twitter).

Search of data from existing systematic reviews and umbrella reviews
We reviewed the reference lists and data extracted for the umbrella review to identify relevant primary studies that could serve as further examples. We also searched a previously published systematic review conducted using machine learning, which employed a broad search strategy to identify all the literature that discussed climate and health.[17] The search yielded more than 16,000 studies and included studies on the impact of climate change on health, as well as health as co-benefits to climate change adaptation and mitigation actions. Studies were given a relevance score from zero to one for each of the three categories, zero being of least relevance and one being of highest relevance. We ordered the relevance score and began screening studies from highest to lowest relevance. No additional studies were identified beyond the relevance score of 0.5, and a decision was made to stop screening at relevance score 0.3.

Hand search
We conducted hand search of websites of organisations and climate change projects that are known to the Pathfinder Initiative team. We also examined the reference lists of included documents or published articles to identify other potentially relevant studies for inclusion. Finally, for reports that summarised multiple implemented mitigation actions were traced back to their source for more information.

Table A2.1 – Submission names and locations to the Pathfinder Call for Evidence. All submissions were reviewed for inclusion and contacted post submission to follow up with further questions and with feedback on the submission. We thank all those who submitted case studies to our call.

Submission Name	Location
Family Planning, Environmental Conservation, and Resilience	Tanzania
Supporting bike use	Belgium
The Bruxell'AIR bonus	Belgium
Peas Please	UK

Reducing Harmful Vectors by implementing immemorial systems: Example of the Seguias in Tameghza	Tunisia
Labos 1point5 – Reducing the environmental footprint of research activities	France
Carbon footprint of the Austrian health sector	Austria
APCC Special Report “Health, Demography and Climate Change”	Austria
Sustainable school meals	Finland
Victorian Healthy Homes Program	Australia
Sustainable food systems in Indian Healthcare Sector	India
After evaluation, Mexico City transforms pop-up bike lane in landmark avenue into a permanent one	Mexico
Biochar-based fertilizer for small-scale farmers	Bangladesh
Brussels: 40 km of pop-up bike lanes	Belgium
Steps towards Net Zero health operations of the Aga Khan Health Services (AKHS) and widening impact through partners	Multiple
Agricultural Carbon Program	Canada, USA
Módulo Agroecológico. Ganadería de pastizal	Argentina
Canada Coal Phase out	Canada
Supporting a National Price on Carbon	Canada
Nature-based Solutions in Campinas, Brazil	Brazil
TransformTO: Climate Action for a Healthy, Prosperous, Equitable Toronto	
Health and environmental co-benefit behaviours for mitigation of climate change by reducing greenhouse gas emissions in urban China	
Ecosystems and Human Health: The Local Benefits of Forest Cover in Indonesia	
Electricity savings and greenhouse gas emission reductions from global phase-down of hydrofluorocarbons	
Climate change of further pig and poultry production	
Consequences of climate change for the spread of invasive vectors and vector borne diseases in Austria (and neighbouring regions).	
Climate and health co-benefits from changes in urban mobility and diet: an integrated assessment for Austria Part I: Mobility	
New Options for Resilient Measures for human health and well-being in the construction industry under climate change in Austria	
Evaluating the effects of climate warming and precursor emission changes on the attainment of the Austrian ozone standard	
Using animation to cultivate optimism, innovation, belief and passion to improve climate change and health outcomes for all.	
Enhancing adaptation and resilience through re-vegetalisation of school yards	Belgium
Gender	
Climate change and public health in Rio De Janeiro City - Brasil: Warning System.	Brazil

Brazilian Environment and Health Olympiad	Brazil
Isfahan Smart City - Stage 1: Smart City Transformation Plan	Iran
Missions València 2030	Spain
Arthritis Rehabilitation through the Management of Exercise and Diet (ARMED)	Ireland
Mapa de Movilidad	Mexico
Textile Swapping	Scotland

A3: Expanded harmonisation from Umbrella Review.

After data extraction, the quantitative estimates of GHGs and health outcomes (or risk factors) were harmonised according to temporal and spatial scales and units of measurement, in order to generate comparable estimates of changes in tonnes of GHGs per capita (in CO_2eq and for separate gases where feasible) and changes in Years of Life Lost (YLL) per 100,000 population over a period of one year if the studied actions were scaled up as far as possible to the national level of the country in which the study was undertaken. Spatial scale-up was performed according to the best estimates available in each case, for example farm-level studies were scaled up based on the number of farms of the same type in the country, whereas city-level studies were scaled up based on the urban population of the country. Other population-based studies were scaled up to the national population in the relevant year. Temporal scale-up assumed that effects would be linear over time, and health outcomes in raw deaths, mortality rates and DALYs were converted to YLL using country- and cause-specific estimates from the GBD.[12,13] Where YLL were unavailable for an action but both mortality and DALYs were reported, an average was taken of their estimated YLL (mortality and DALYs usually over- and underestimate the magnitude of YLL, respectively).

Some studies only had health exposures available, rather than outcomes, which required modelling to mortality. For air pollution, changes in pollutants were either given in terms of concentrations or absolute weights and data had initially been extracted for NO_2, NO, NOx, NO_3, PM10, and PM2.5. For the former, the AirQ+ tool developed for WHO Europe was used. The tool allowed long term health impacts of PM2.5, PM10, and NO_2 to be evaluated using a life table approach, requiring the area under study and all-cause mortality incidence in adults over 30 to be entered into the tool (estimated by the GBD ref). Estimated mortality attributable to the pollutant was then converted to YLL.

For NOx and PM2.5 reported in change in kg, we used the CLIMAQ-H tool also developed for WHO Europe. This tool can convert emissions of NOx and PM2.5 directly to deaths and YLL by estimating changes in exposure not only in the emitting country but also neighbouring countries in the WHO European region. The version of the tool used for this analysis is in beta and included health outcomes for the USA and China as well as European countries. Around 60 primary studies (mostly agricultural studies) which were initially extracted were removed from the analysis at this stage due to the available tools not being able to model NO and NO_3.

Panel A1. Example calculation for converting a study estimate to YLL/100,000/year and GHG/100,000/year.

For example, Cifuentes et at. (2001) considered energy efficiency and fuel substitution policies in transportation, energy, residences, and industry, which were evaluated in a Chilean study to be of minimal cost and lowered GHG emissions in 2020 by 13% with respect to a forecast 2020 business as usual. These policies were considered for the following cities: Sao Paulo, Mexico City, Santiago, and New York. For Sao Paulo, the predicted change in deaths in the city over 20 years (2001-2020) from PM10 and O3 was -4280 and -293, respectively.
Additional information we collected was:

- Chile population in 2020 (year of study closest to present day): 19,116,209
- Santiago city population in 2020: 4,837,295
- Urban population of Chile in 2020: 16,770,077
- GHG emissions from the energy, transport, residential, and industrial sectors in Santiago city in 2020 (estimated): 21,732,112 tonnes CO_2eq
- GBD conversion factor between mortality and YLL due to ozone in 2020 in Chile: 18.94
- GBD conversion factor between mortality and YLL due to PM10 in 2020 in Chile: 19.04

Thus, *change in GHGes in Santiago in 2020* is:
21,732,112 x 0.13 = reduction of 2,825,175 tonnes CO_2eq
Scaled such that this change took place in all *urban areas of Chile*:
2,825,175 * (16,770,077/4,837,295) = 9,794,399
Per 100,000:
(9,794,399/19,116,209)*100,000 = **reduction of 51 kilotonnes CO_2eq/100,000/year**
While the *change in deaths in Santiago in 2020 from PM10* is:
4,280/4,837,295/20 = 4.42 $x10^{-5}$
For all of Chile:
4.42 $x10^{-5}$ *(16,770,077/19,116,209)*100,000 = 3.88 fewer deaths / 100,000 people
And YLL:
3.88 * 19.04 = 73.88 fewer YLL / 100,000
And the *change in deaths in Santiago in 2020 from PM10* is:
293 /4,837,295/20 = 3.03 $x10^{-6}$
For all of Chile:
3.03 $x10^{-6}$ *(16,770,077/19,116,209)*100,000 = 0.27 fewer deaths / 100,000 people
And YLL:
3.88 * 18.94 = 5.03 fewer YLL / 100,000
Making the total: **79 fewer YLL (or years of life *gained*)/100,000/year**

We also calculated standardised co-impact intensities to test the utility of the metric (e.g. YLL/100,000 population/year/CO2eq). We chose not to use these standardised ratios in our main results, as they would have given the greatest weighting to actions where there were large health benefits but small GHG mitigation benefits (or vice versa depending on the measure chosen as the denominator). For example, actions to promote active travel (walking and cycling) in the transport sector tend to have large health benefits but modest reductions in greenhouse gas emissions, and so their ratio of health benefits to GHG benefits would be high, however their impact on total GHG emissions is relatively small. By contrast, actions to change diets can have large benefits for both health and emissions reduction and using a ratio would make the benefits of these actions appear smaller when compared to transport (Figure A3.1).

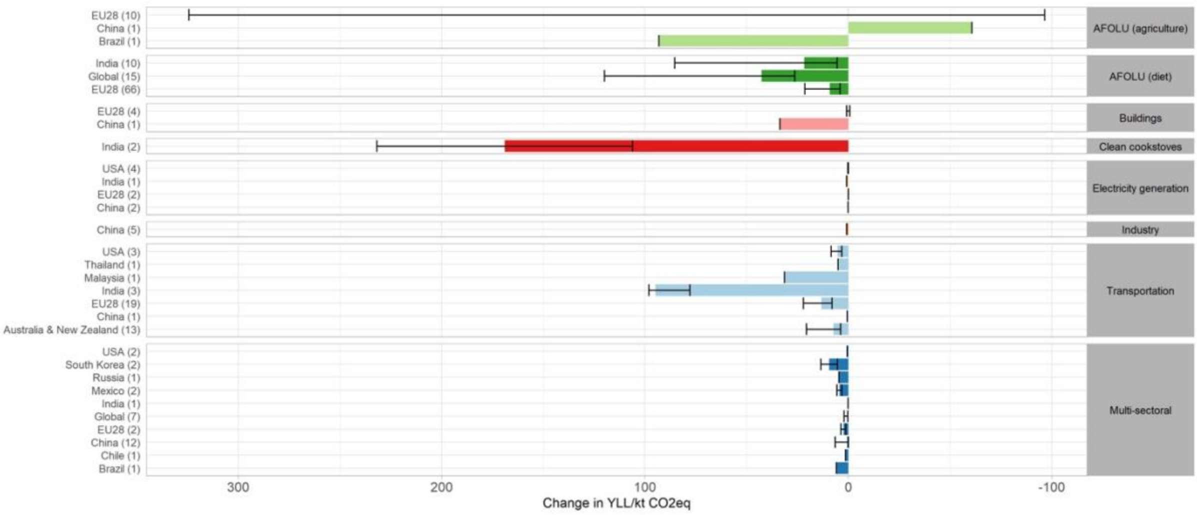

Figure A3.1. ratios of health co-impacts to mitigation potential for each action, i.e. the number of years of life gained/100,000 per year per tonne of greenhouse gas emissions (CO_2e) avoided

A4: Umbrella Review - Excluded Studies

78 studies were excluded after data extraction for either not having enough information to scale up to the national level (e.g. small-scale soil incubation studies), not having a clear 'business as usual' (such as a standard fertiliser level), or for having health data that we could not model to YLL (such as NO and NO3). Of these, 58% were from HICs, 35% were from UMICs (primarily agricultural studies from China focusing on the release of NO or NO3), while only 3% were from LMICs (Table A4.1 and A4.2). None were from LICs, reflecting the wider lack of evidence available from, and lack of inclusion in systematic reviews of studies from LICs. Compared with the proportion of UMICs included in our review, a substantial proportion were excluded after data extraction. However, this is largely due to the type of data they collected – mostly farm level studies measuring gases like NO and NO3 (69% of UMICs which were excluded), which we could not model to health outcomes. The final proportions of unique mitigation actions from each sector included are presented in Figure A4.1

Table A4.1

Sector and Scale	Count of excluded studies
Global	**3**
AFOLU	2
energy	1
HIC	**45**
AFOLU	43
Transport	2
LMIC	**2**
AFOLU	1
human settlement	1
OECD	**1**
AFOLU	1
UMIC	**26**
AFOLU	18
energy	1
industry	1
Transport	2
Transport, industry, building	4
UMIC* in 2020	**1**
AFOLU	1
Total	**78**

Table A4.2: Number of studies excluded after the data extraction stage, by income level of country. *According to World Bank classification.

Country income level*	# Studies excluded
Global	3 (3.8%)
HIC	45 (57.7%)
LMIC	2 (2.6%)
OECD	1 (1.3%)
UMIC	27 (34.6%)
Total	**78**

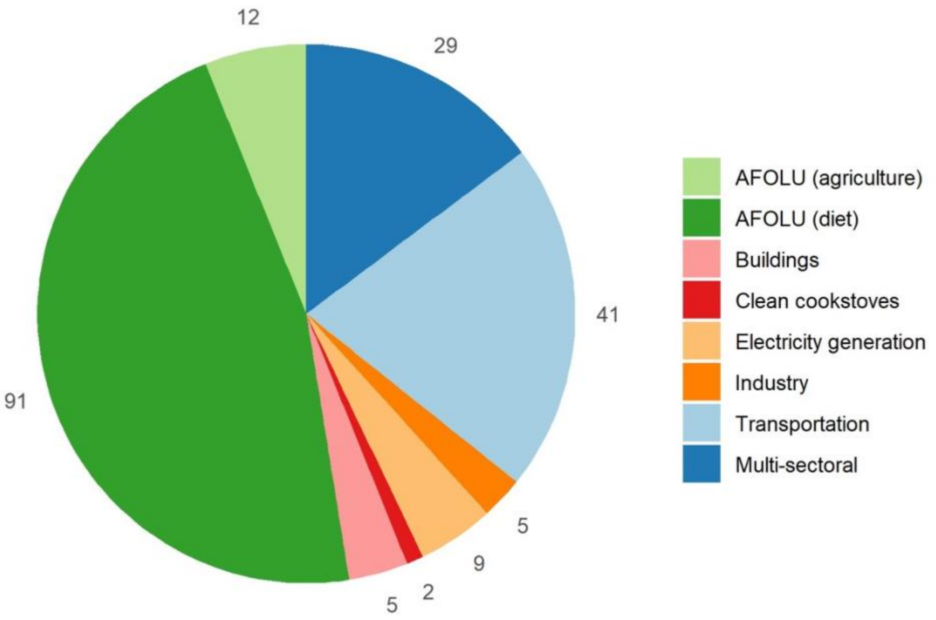

Figure A4.1. Proportion of unique mitigation actions from each sector.

Table A4.3. Average YLL/100,000/year for LIC, LMIC, UMIC, HIC, and Global settings, weighted by constituent countries' population size for different pathways to health outcome (YLL). Estimates are derived for 2019 and available from the GBD. *According to World Bank classification.

Pathway to health	Country income level*	YLL/100,000/year		Pathway to health	Country income level*	YLL/100,000/year
Air pollution	LIC	4,540		Low physical activity	LIC	53
	LMIC	3,260			LMIC	140
	UMIC	1,882			UMIC	197
	HIC	533			HIC	219
	Global	2,482			Global	164
Dietary risks	LIC	1,093		Road injuries	LIC	929
	LMIC	2,135			LMIC	718
	UMIC	2,595			UMIC	803
	HIC	1,916			HIC	444
	Global	2,163			Global	724

A5: Example Exposure-Response Functions

Despite the large potential for GHG mitigation and health co-benefits from reduced air pollution in China,[18–20] our included studies did not show large reductions in YLL. Markandya (2009), however, found a health co-benefit intensity of -54 YLL/100,000/year for policies aimed at decarbonising the electricity generation sector in China[21] (see main report Figure 7). Markandya et al used a stepwise log-linear and log-log model to estimate the effect of PM2.5 on mortality. By contrast using the WHO's Comparative Risk Assessment (CRA) method for the same study would have resulted in an estimate of c.500,000 fewer YLL country-wide in the study year. Log-log models were proposed to avoid unrealistically high health impacts at high levels of pollution, however Pozzer et al. (2023) noted that these functions may not be representative for highly polluted regions, like China, thus underestimating the health benefits to reductions in air pollution.[22]

Peng et al. (2018), who estimated the impact of air quality measures, electrification, and decarbonised electricity across the electricity generation, transportation, and building sectors of China (main report Figure 8), uses ERFs based on the GBD.[23] In line with recent literature on the potential for the GBD to underestimate air pollution impacts,[22] it is likely that this, too, is an underestimate. A national energy efficiency policy in China considered by He et al. (2010) found relatively small health co-benefits[24] (Figure 8). They used the US-EPA's BenMAP model to estimate health benefits, where the ERFs were linear or log-linear.

An improved relative risk Fusion model has been developed that incorporates features of existing models while addressing their limitations and is suitable for use in health benefits analysis. Wider use of this model could allow more realistic estimates of air pollution health co-benefits of climate change mitigation actions.[25]

A6: Nature Based Solutions – Methods and Full Results

Background
This was a scoping review of publications that conducted primary analysis to examine the mitigation potential of nature-based solutions (NBS) alongside health and socio-economic co-benefits. We used the IUCN working definition of NBS *"actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits".*[26] Natural Climate Solutions (NCS) are a subset of NBS that can be employed to limit warming by reducing atmospheric greenhouse-gas concentrations.[27,28] They form the three steps to achieve climate benefits marked by: i) protecting ecosystems and thus reducing carbon release for example by halting deforestation ii) restoring ecosystems so that they sequester carbon and iii) sustainable landscape management to reduce emissions and increase sequestration.[27] These solutions work alongside ambitious decarbonisation solutions discussed elsewhere in this report, to offer an additional contribution to climate mitigation to limit temperature rise and achieve the Paris Agreement target of 1.5^{o}C.[29,30] All study designs (quantitative and qualitative) were included in the screening, as were studies where the reported outcomes were modelled or observed.

Methods
We identified relevant publications in the following way:

- Searching through pre-existing databases (DFID and C40) that have collated studies on actions to reduce greenhouse gas emissions. We then filtered out publications where the focus was on nature-based solutions and systematically screened for papers that reported health and/or socio-economic impacts.
- Searching databases that collate studies related to NBS or the natural environment (Ignition Project and Nature Based Initiative online tool). Here we filtered out publications that reported reduction in greenhouse gas emissions as a sole outcome.
- Contacting specific authors to request recent updates to studies that we thought were relevant, but there was scope for more analysis to be done – for example, some of the urban ecosystem studies had quantified a reduction in tropospheric ozone and it was plausible that follow-up studies could have also quantified CO2 reductions. Similarly, for studies that conducted qualitative assessments we inquired complementary quantitative measures.
- Following up on relevant references from the studies obtained using the above processes as well as other key publications that were deemed relevant by the project team and the commissioners (such as the WHO Synthesis of Evidence).

The literature search was concluded when we reached a point of saturation whereby further literature search did not yield any additional studies. All manuscripts were double screened to check for measured or modelled greenhouse gas outcomes and one of more of the following: measured or modelled health outcomes, or health exposures such as air quality, or socio-economic determinants of health such as livelihood. Greenhouse gases other than CO2 were considered for in this review, in particular, ozone mitigation potential of urban ecosystems was quantified in several studies and this was included in our synthesis under both impact on health and impact on GHG reduction. The final manuscripts were reviewed, and data was extracted for a narrative synthesis. The range of study designs and inclusion of both modelled and evaluated examples precluded the possibility of conducting a meta-analysis.

Table A6.2 Studies linking modelled and implemented NBS with health exposures and outcomes were identified

Modelled or evaluated		Study	NBS and method of measuring mitigation	GHG Mitigation	Units	Health/SE outcomes	Notes
1	URBAN	Soares, 2011	41,247 trees in Lisbon	CO_2 storage	21,030 tonnes	1) Air quality benefits from pollutant uptake (NO_2, SO_2, O_3, and PM1O) given in kgs removed 2) decreased pollutant emissions from power plants because of energy savings 3) potential disbenefit of BVOC emissions from trees on ozone air quality 4) Increase in property value (trade-off) 5) storm run-off reduction	Reduction of air pollutants = 25.6 t annually, valued at $222,738 or $5.40/tree [estimated as value that society places on clean air, as indicated by its willingness to pay for pollutant reductions]
Mixed - field inventory (tree species) and modelling			i-tree tool	CO_2 sequestered	1776 tonnes per growing season		
				CO_2 avoided	633 tonnes		
				Carbon released e.g. during tree maintenance or decomposition	549 tonnes (maintenance and decomposition)		
2	URBAN	Sunderland, 2012	818,000 trees in Torbay	CO_2 storage	98,1000 tonnes or 15.4 tonnes/ha	1) Air quality benefits from pollutants uptake (O_3, PM10, NO_2, and SO_2) tonnes/per year	Health/well-being impacts estimated as £1.33 million per year -[unclear how this was estimated]
Modelling			i-tree tool	CO_2 sequestered	3,320 tonne/year		
				CO_2 avoided	not reported		
				Carbon released e.g. during tree maintenance or decomposition	959 tonnes/yr due to tree death		
3	URBAN	Millward, 2017	309 urban trees in Toronto	CO_2 storage	not reported	1) Air quality benefits from pollutant uptake (O_3, NO_2, PM10, and SO_2) in kg/year? 2) energy savings from tree shading and wind breakers	Air pollutant reduction valued at $1520 annually [estimated using the marginal cost of controlling different pollutants required to meet air quality standards] Energy savings valued at $36/tree ($1190 for electricity and $9914 for natural gas)
Mixed - field inventory (tree species) and modelling			i-tree tool	CO_2 sequestered	27,201 kg/year		

				CO_2 avoided	32,193 kg/year e.g., from power plants		
				Carbon released e.g., during tree maintenance or decomposition	7500 kg/year		
4	URBAN	Flynn, 2013	Bioinfiltration rain garden Villanova Uni, # of trees not provided	CO_2 storage	490 kg per year?	1) air pollutant removal (NO_2, PM10, SO_2, 03, CO) in kg 2) negative human health impacts during construction phase which are positive during operation phase: Global warming potential (kg CO_2 eq.), human health – cancer (kg benzene eq.), eutrophication (kg N eq.), eco-toxicity ((kg 2,4-D eq.), respiratory effects (kg PM2.5 eq.), smog formation potential (kg Nox eq.)	
Implemented - Mixed - field inventory (tree species) and modelling				CO_2 sequestered	40 kg per year		
				CO_2 avoided (Annual avoided global warming potential)	1943 kg CO_2 eq/year		
			i-tree tool	Carbon released e.g. during tree maintenance or decomposition	not reported		
5	URBAN	Szkop, 2016	932 trees in Warsaw park	CO_2 storage	not reported	Air pollutant removal (NO_2, PM2.5, 03, and SO_2) kg/year	Air pollution benefits [estimated as avoided health costs] $5857/year. PM2.5 accounting for 69% of this
Mixed - Field inventory (tree structure and species) and modelling			tree inventory and algorithm	CO_2 sequestered	not reported		
				CO_2 avoided	not reported		
				Carbon released e.g during tree maintenance or decomposition	not reported		
				O3 removal	149.9 kg/year		
6	URBAN	Nowak, 2006		CO_2 storage removal?	not reported		

Modelled			All urban trees in the US	CO_2 sequestered	not reported	Air pollutant removal of NO_2, O_3, SO_2, PM10 and CO	Total pollution air removal (5 pollutants) by **urban** trees in coterminous United States is estimated at 711,000 t, with an annual value of $3.8 billion
				CO_2 avoided	not reported		
				Carbon released e.g. during tree maintenance or decomposition	not reported		
				O_3 removal	305,100 t/ year		
7	URBAN	Donovan and Butry, 2009	Trees across 460 households in Sacramento California	CO_2 storage	not reported	Summertime electricity usage measured in kWh	Trees on the west and south sides of a house reduce summertime electricity use by 185 kWh (5.2%), whereas trees on the north side of a house increase summertime electricity use 55 kWh (1.5%). A London plane tree, planted on the west side of a house, can reduce carbon emissions from summertime electricity use by an average of 31% over 100 years
Mixed - GHG modelled, health outcomes measured from field inventory				CO_2 sequestered	not reported		
				CO_2 avoided (through energy savings and sequestration)	29.8 Mg/ tree/ 100 years		
				Carbon released e.g during tree maintenance or decomposition	not reported		
8	URBAN	Kovacs, 2013	Street trees in New York's state public land	CO_2 storage	not reported	Reduced buildings energy consumption	Depending on the species planted, the cost of reducing carbon, averaged across planting locations, ranges from $3133 to $8888 per tonne carbon. The London plane tree is the most cost-effective species because of its long life span and large canopy, and the marginal cost of carbon reduction for the species ranges from $1553 to $7396/tC across planting locations
Modelled				CO_2 sequestered	not reported		
				CO_2 avoided (through energy savings)	discounted tree abatement - 6.53 tons/carbon (t/c) per tree across 100 years, of which 0.96t/c is from cooling savings and 5.57 t/c is from heating savings		
				Carbon released e.g. during tree maintenance or decomposition	1.56 tC per tree per 100 years		

9	URBAN	Naumoski, 2016	Hypothetical scenario of planting 555 trees in Skopje, Macedonia	CO2 storage	548.86 kg/ year	Air pollutant removal of O3, PM10, SO2, NO2 and PM10 and avoided VOCs Emissions of harmful BVOCs Rainfall interception Energy savings	
Modelled				CO2 sequestered	not reported		
				CO2 avoided	not reported		
				Carbon released e.g. during tree maintenance or decomposition	not reported		
10	URBAN	Pothier, 2013	Eight contiguous city blocks located in the downtown core of Toronto (584 trees)	CO2 storage	55,005 kg/ year	Air pollutant removal of O3, PM10, SO2 and NO2 Storm water run-off mitigation Energy savings from buildings	Air pollutant removal was estimated to total 136 kg per year. There were variations by species and by pollutant The urban trees intercepted an estimated 1435 m3 of storm water runoff in 2009. The urban forest was estimated to have conserved 1093 GJ/yr of energy in 2009 through shading, evapotranspiration and windbreak. Natural gas savings were estimated at 1015 GJ/yr, and conserved electricity totalled 78 GJ/yr
Mixed - Field inventory (tree structure and species) and modelling				CO2 sequestered	9.98 tonnes/ year. Norway maple trees, green ash and crab apple were the most important carbon-sequestering species		
				CO2 avoided	not reported		
				Carbon released e.g. during tree maintenance or decomposition	not reported		
11	URBAN	Derkzen, 2015	Urban trees in Rotterdam, Netherlands	CO2 storage	41.97 kg/ m2	Air pollutant removal Storm water run-off mitigation Energy savings from cooling Noise reduction Recreation	
Modelled				CO2 sequestered	not reported		
				CO2 avoided (through energy savings)	not reported		
				Carbon released e.g. during tree maintenance or decomposition	not reported		
12	URBAN	McPherson, 2017		CO2 storage	2. MMT CO2		

Mixed - Field inventory (tree structure and species) and modelling			All 173 million urban trees in California	CO2 sequestered	7.2 MMT CO2 per year	Air pollutant removal of O3, PM10, SO2, NO2 and PM10 and avoided VOCs Emissions of harmful BVOCs Stormwater run-off mitigation Energy savings (cooling and heating) Increase in property value	
				CO2 avoided	1.3 MMT CO2 per year (from buildings energy savings)		
				Carbon released e.g. during tree maintenance or decomposition			
14	URBAN	McPherson, 2005	5 US cities: Ft. Collins, Cheyenne, Bismarck, Berkeley and Glendale	CO2 storage	Cheyenne, 120lb per year	Air pollutant removal of O3, PM10, SO2, NO2 and PM10 and avoided VOCs Emissions of harmful BVOCs Stormwater run-off mitigation Energy savings (cooling and heating) Aesthetics and Other Benefits Increase in property value	In Cheyenne, the average per tree avoided emissions (132 lb) from energy savings exceeded sequestered CO2 (121lb) because of, largely, high percentages of coal in electric power plant fuel mixes.
Mixed - Field inventory (tree structure and species) and modelling				CO2 sequestered	varied by city, highest in Cheyenne and Bismarck (228 and 204lb per tree)		
				CO2 avoided	Cheyenne, 132lb per year		
				Carbon released e.g. during tree maintenance or decomposition	not reported		
15	URBAN	Grzędzicka, 2019	Urban trees in Silesia park, Poland	CO2 storage		Air pollutant removal of PM2.5, PM10	
Field experiment				CO2 sequestered			
				CO2 avoided			
				Carbon released e.g. during tree maintenance or decomposition			
1	URBAN AND RURAL	Nowak, 2014	Trees and forests in the	CO2 storage	not reported	Air pollution removal of NO2, O3, PM2.5 and SO2	Trees and forests in the conterminous United States **(both rural and urban)** removed 17.4 million tonnes (t) of air pollution in 2010 with human

Modelled			conterminous US	CO2 sequestered	not reported		health effects valued at 6.8 billion U.S. dollars. Health impacts included the avoidance of more than 850 incidences of human mortality and 670,000 incidences of acute respiratory symptoms. Most of the pollution removal occurred in rural areas, while most of the health impacts and values were within urban areas.
				CO2 avoided	not reported		
				Carbon released e.g during tree maintenance or decomposition	not reported		
				O3 removal	14,330,000 tonnes pe year		
1	RURAL	Pandey, 2015	105 community forests in Nepal ~10K ha	CO2 storage	increased by 5.1 MgC/ha/yr as a result of sequestration	fodder and grass for livestock timber to build houses, fuel wood for household energy consumption of wild food (fruits, vegetables and meat) income from selling nontimber forest products	
Mixed - Tree data modelled and health outcomes obtained through FGDs				CO2 sequestered	48.2–129.9 MgC/ha (between 2010 - 2013)		
				CO2 avoided	not reported		
				Carbon released e.g during tree maintenance or decomposition	not reported		
2	RURAL	Mekuria, 2015	11 community enclosures in Ethiopia - 1483 ha tree inventory and algorithms	CO2 storage	not reported	Community revenue from carbon market. The net present value (NPV) of the aboveground carbon sequestered in exclosures ranged from US$6.6 to US$37.0 per hectare and increased with exclosure duration. At a watershed level, 51.4 Mg C ha-1 can be sequestered, which	Other associated benefits: reduced land degradation and soil erosion increased food production, fodder availability and improved livelihood
Implemented - Field experiments (tree inventory) modelled across years and household surveys (historical recall)				CO2 sequestered	51.4 MgC/ha sequestered from the 11 exclosures, representing 188.6MgCO2/ha		
				CO2 avoided	not reported		

				Carbon released e.g. during tree maintenance or decomposition	not reported	represents 188.6 Mg CO2 ha-1, resulting in temporary certified emission reductions (tCER) of 139.4 MgCO2 ha-1 and NPV of US$478.3 per hectare.	
3	RURAL	West, 2018	513 ha deforestation frontier, Amazon	CO2 storage	not reported	Equity implications scenarion 1- increased farm-based profits by average of 8% (0% in the poorest and 25% in the wealthiest) scenario 2- increased farm-based profits by an average of 335% (79% in the poorest to 617% in the wealthiest).	
Modelled				CO2 sequestered and CO2 avoided - simulated the potential impacts of REDD+ payment scenarios on net CO2 not emitted or removed from the atmosphere (Mg CO2−1), and community welfare (farm-based household profits)	scenario 1 - $15 Mg CO2−1 which equates to preserving 70% of mature forests scenario 2- $30 Mg CO2−1 which assume preserving virtually all (97%) mature forests		
			modelled scenarios	Carbon released e.g. during tree maintenance or decomposition	not reported		
4	RURAL	Pauydal, 2016	Phewa watershed in Nepal.	CO2 storage	not reported	Provision of raw materials, recreation and ecotourism, freshwater provision and sediment retention	Assessment of the supply of ecosystem services across the Phewa watershed, and comparing dense, sparse forests, grasslands and agricultural landscapes
Mixed - Tree data modelled across time, and health outcomes obtained through stakeholder workshops				CO2 sequestered	not reported		
				CO2 avoided	not reported		
				Carbon stocks	Between 50m3/ ha-1 to 100 m3/ ha-1, based on type of habitat		
				Carbon released e.g. during tree	not reported		

				maintenance or decomposition			
5	RURAL	Fedele, 2018	Land-use changes in West Kalimantan and Central Java - Indonesia	CO2 storage	not reported	Products from the land - food and tree-based resources such as rubber, timber, medicinal products and others Water quality	Estimating the impact of adaptation land-use strategies on the supply of ecosystem services by comparing different benefits related to products, water, carbon, and biodiversity. Four land-uses were evaluated: agroforestry, forest conversion, forest protection and reforestation. Trade-ofs between regulating and provisioning services were reported
Mixed - Tree data modelled across time, and health outcomes obtained through FGDs (historical recall)				CO2 sequestered	not reported		
				CO2 avoided	not reported		
				Carbon stocks	Varied by the type of habitat: semi-natural protected forests - 198 tC/ ha logged over forest - 130 t C/ha gardens - 15 t C/ha croplands and 2 t C/ha Trees integrated with croplands - 49 t C/ha		
				Carbon released e.g. during tree maintenance or decomposition	not reported		
6	RURAL	Wood, 2016	Climate Compatible Development projects in Malawi	CO2 storage/savings	combined CO2 savings reported as 4,475,744 t/ over 50-years. This includes avoided emissions from use of cookstoves, solar lights and carbon stocks from forestry activities	Income, food security, diet, access to firewood, children education, smoking related illness, climate resilience, household assets, access to emergency funding	This article develops a framework to enable assessment of climate compatible development outcome over seven parameters identified. And explore the outcomes of two donor-funded projects that pursue climate compatible development triple-wins in Malawi using the framework.
Implemented - Mixed, GHG modelled and health outcomes via stakeholder surveys and				CO2 sequestered	not reported		

interviews (historical recall)							
				CO_2 avoided	as above		
				Carbon released e.g. during tree maintenance or decomposition	not reported		
7	RURAL	Brown, 2010	Natural regeneration of 2,728ha of degraded forests using FMNR	CO_2 storage	not reported	Food security, flood mitigation, livelihood benefits	Clean Development Mechanism (CDM) allows countries to trade emissions offsets. The CDM has the dual goals of reducing overall greenhouse gas emissions, as well as promoting sustainable development. Agroforestry methods, including FMNR, can play a critical role in addressing poverty, food security and climate adaptation. Revenues generated from carbon credit trading can support livelihoods and help meet SDGs
Implemented - mixed (GHG modelled, health outcomes via personal communication)				CO_2 sequestered	165,000 tons over 10 years		
				CO_2 avoided	not reported		
				Carbon released e.g. during tree maintenance or decomposition	not reported		
8	RURAL	Peh, 2014	Converting drained, intensively farmed arable land to a wetland habitat in the UK	CO_2 storage	not reported	Livelihood benefits: - nature-based recreation through the direct expenditure by visitors to the restored wetland - from grazing through commercially priced agreements - flood protection (USD 48 per ha/per year). - substantial net loss of arable land for crop production which was estimated as USD 2037 per ha/per year.	A rapid assessment of changing ecosystem service values in a UK wetland. The study used the Toolkit for Ecosystem Service Site-based Assessment (TESSA) to evaluate the ecological benefits and monetary values of ecosystem services provided by the 479ha restored wetland mosaic in comparison to the former arable land.
Implemented - modelled ecosystem services assessment				CO_2 sequestered	479ha of restored wetland had an estimated annual global warming potential of 809 tonnes CO_2		
				CO_2 avoided	not reported		
				Carbon released	Arable land emitted 2,323 tonnes CO_2 equivalent (eq)		
9	RURAL	Scriven, 2012		CO_2 storage	not reported		

Implemented - GHG modelled, health outcomes via household surveys			REDD plus in the Peruvian Amazon	CO2 sequestered	Modelled using average rate of sequestration through reforestation of tropical forests	Income diversification and forests products	Compares small holder land use and livelihood strategies at the forest-farm frontier in the Peruvian Amazon. Four REDD strategies are compared including payment for ecosystem services
				CO2 avoided	not reported		
				Carbon released e.g. during tree maintenance or decomposition	not reported		

A7: Case Study: Sanitation – Surat, India

Between 1995 and 2011, the Surat Municipal Corporation (SMC) made large investments in the water supply infrastructure in Surat, India. The city expanded the coverage of the piped water supply network and the sewerage network including upgrading existing treatment plants. The upgraded plants use an anaerobic sewage treatment that enables the capture and use of methane for power generation. The project resulted in a reduction of 80,000 tonnes of CO_2eq emissions per year from four sewage treatment plants.[31] It has also resulted in improvements in the water quality, measured in terms of declines in the Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD) and Suspended Solids (SS) indicators. However, the Total Dissolved Solids (TDS) remained high, which was likely to be due to chemical treatment (chlorination) of water before discharging it to the water bodies. In addition, from 2009, the four sewage treatment plants produced 3000 to 5000 tonnes of organic manure per year, generating a total revenue of approximately 2.5 million Indian Rupees (INR) per year and a total of 32 new jobs were created across the four plants.

An investigation in India found that the most important driver for wastewater treatment and water reuse is water scarcity, indicating a need for water reuse solutions to help meet population demands for water supply.[32] In contrast, important barriers include inadequate collaboration between central and state governments and between different water-related ministries; lack of an umbrella directive for integrated water resources management, with no clear action plans to operationalise policies promoting wastewater management; and finally, weak enforcement and monitoring mechanisms. A few Indian states, such as Maharashtra, Punjab, or Gujarat (where Surat city is located), have been able to define reuse standards and establish successful wastewater treatment and reuse approaches supported by long-term financing mechanisms. They established an effective governance structure, which ensures that regulations are enforced and monitored.

The city of Surat treats a total of around 1,400 million litres per day (MLD) of sewage water, of which 320 MLD (33%) is reused. If the sewage treatment approach discussed here were to be scaled up to the entire volume of wastewater produced in Surat, annual savings of approximately 240,000 tonnes of CO_2eq could be achieved in the city. It is estimated that approximately 38,000 MLD of sewage is generated in major cities in India. Therefore, applying this approach of sewage treatment to all major cities in India could potentially save about 6.5 Mt of CO_2eq annually. This will also have positive effects for human health, as currently, the leading cause of water pollution in India is untreated wastewater discharged into surface as well as groundwater.

A8: A systemic lens for opening the door to sufficiency

The OECD Systems Innovation for NetZero process, for example, aims at understanding what policies can bring systemic change (i.e. change the system structure) so as to trigger large behavioural change and in this way achieve more sustainable (including by reducing emissions and improving health) outcomes. The *Transformative change case study: Irish transport sector* in the main report describes the practical application of the OECD System's Innovation for NetZero process to assess implemented and planned Irish policies aimed at achieving mitigation goals for the transport sector. The process was developed with the aim of supporting policy makers in taking a systemic approach and identifying policies with high transformative potential, via three steps: 1. Envision the goal(s) and the patterns of behaviour that a properly functioning system would foster, and challenge ingrained mental models underlying poorly functioning systems; 2. Understand why the current system is not achieving the envisioned goals and patterns of behaviour and whether implemented and planned policies have the potential to redesign the system; 3. Prioritise and scale up the policies that can redesign systems to foster desirable patterns of behaviour and goals.

International experience suggests that the implementation of the type of policies identified as transformative via the Irish case study can indeed trigger large behavioural change and with this bring large climate and health benefits.[33] For example, in Pontevedra, a small Spanish town, road reallocation and street redesign, in tandem with a change towards mixed land-use planning has reduced car traffic by 69% in the town centre and 90% in the downtown core. Air pollution and GHG emissions were reduced by 61% and 70% respectively. In addition, while in 1996–2006 30 people died in road accidents in main streets, only 3 have died since 2006 (with no road fatalities after 2009).[34]

For example, Barcelona's Superblocks reorganise the city into polygons of approximately 400 m x 400m. Inner roads are not closed to motorised vehicles, as these can enter the Superblock but they cannot cross it. Cars also have to stay within a speed limit of 10 km/h within Superblocks. The Superblock model liberates 70% of space dedicated to cars while reducing traffic in 15% (by 2024 the aim of the municipality is that traffic reductions could be 21%).[34] Estimates in Barcelona also suggest that if implemented at scale (in the whole of the municipality) the Superblock model could bring relevant results. It is estimated that by adopting this new model in the whole of the municipality, the city could eliminate 36% of GHG transport emissions by 2024 and 45% by 2030. Improvements in air quality would allow 96% of the population to be exposed to air pollution below 40 micrograms / m3. In addition, the model would allow 76% of the population to be exposed to noise below 65 dBA (rather than only 54% of the population).[35]

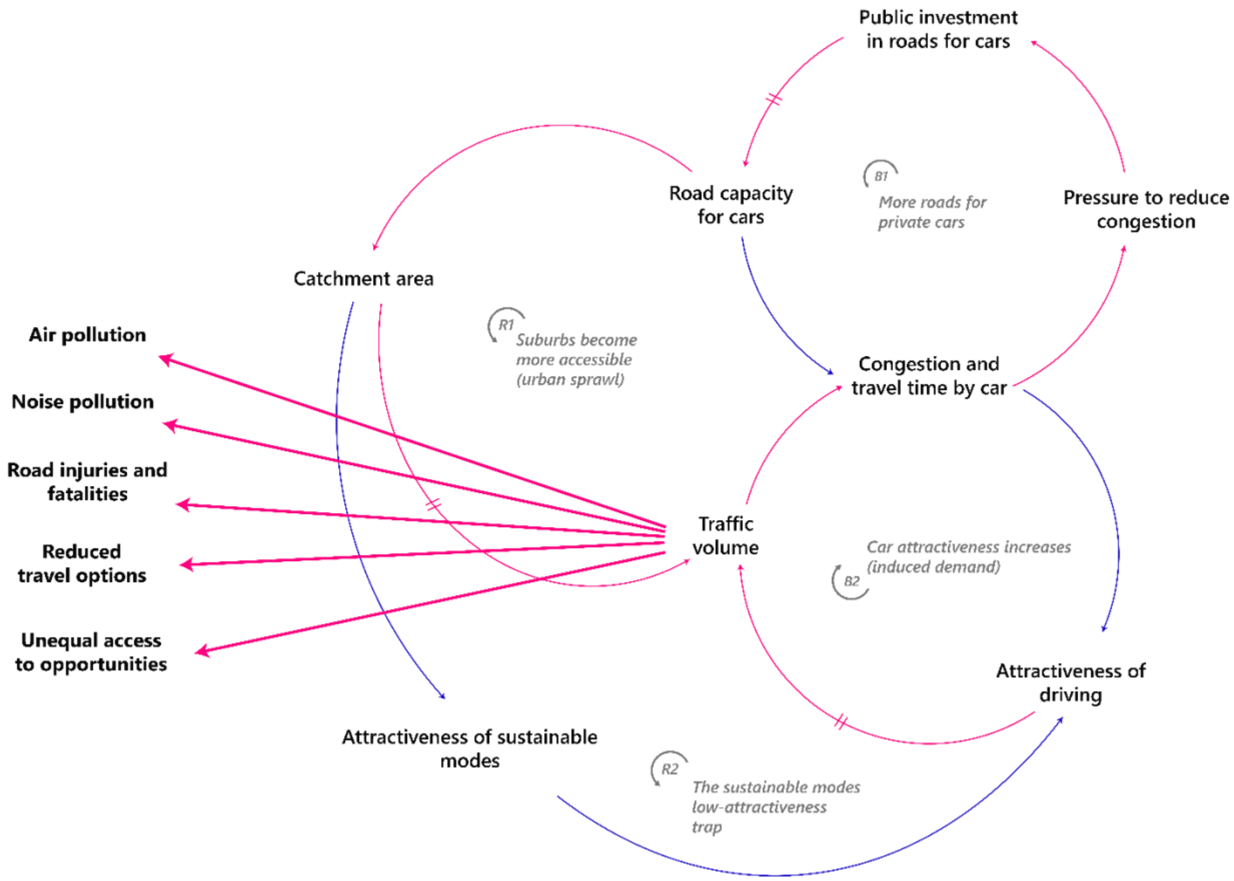

Figure A8.1 System dynamics underlying the car-dependent system and its effects. Induced car demand occurs when public investment in roads for car use causes more, rather than less, traffic congestion. Urban sprawl is the simultaneous dynamic by which people move away from city centres while still commuting to those centres. Both induced car demand and urban sprawl exacerbate the sustainable modes low-attractiveness trap, the third vicious cycle at the source of increased car use and emissions. As more people are induced to drive cars, and policy makers respond by increasing the road capacity for cars, traffic volume of motorised vehicles and the space and funding allocated to them increase, while those allocated to public transport and active modes decrease. As more people move to urban peripheries, daily distances travelled increase and a good transport service becomes difficult and expensive. Active modes are also no longer feasible or competitive options. Unsurprisingly, in this type of system the attractiveness of sustainable modes is low. The coloured arrows show the relationship between variables. A pink arrow between variables means that they vary in the same direction: an increase in a variable leads to an increase in the variable it points at; a decrease in a variable leads to a decrease in the variable it points at. A blue arrow means that variables vary in the opposite direction: an increase in a variable leads to a decrease in the variable it points at; a decrease in a variable leads to an increase in the variable it points at. Each loop label (e.g. B1) denotes a feedback loop. A feedback loop is either reinforcing (R), or balancing (B).

A framework for categorising policies

The OECD analyses policies according to two dimensions: a) policy intent i.e. whether it aims to anticipate and "cope" with car-dependent systems, or whether its aims at transforming the system and shifting it away from car dependency; and b) the potential the policies have to transform the structure of the car dependent system; in other words of reversing each of the three dynamics identified as characterising the car-dependent system (Figure A8.1).

As illustrated in Figure A8.2 reactive and anticipatory policies have low to medium transformative potential since they do not in reality aim to address root causes. The transformative potential of policies with a transformative intent ca however be low, medium, or high depending on the state of the system (e.g. the levels of different stocks) the policy is trying to influence and the policy's scale or level of ambition.

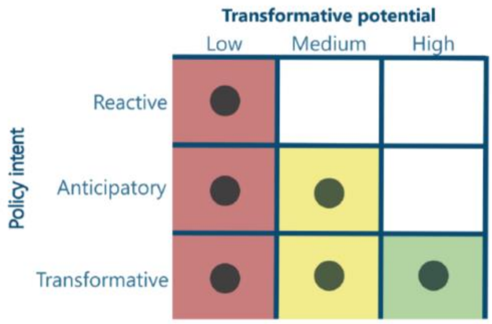

Figure A8.2 Framework for categorising policies according to their transformative potential and intent. Source [33]

The iceberg model is used to identify the policy intent. The iceberg analogy helps illustrate that observed outcomes or events, what we hear on the news (e.g. traffic jams, pollution peaks, road fatalities, growing car use and emissions) are just the "tip of the iceberg". These events (patterns, when observed over time) are the result of systems that have been designed in a certain way and built on dominant mental models. Both the system design or structure and the mental models are "under the surface", invisible to the naked eye. Reactive and anticipatory policies are those that react to events or anticipate patterns (thus focusing on the tip of the iceberg. Policies with a transformative intent are those that aim at changing the system structure or the mental models behind it.

Three systemic tools (see below) are used to identify policies' transformative potential. These tools trigger questions such as whether a policy strengthens or weakens feedback loops, can change a loop's dominance, or lead to the creation of new loops.

- Causal loop diagrams (CLDs) can be seen as a deep dive into the iceberg model's "structure" level, enabling the analyst to better understand the interconnections or causal relationships that produce the results at the tip of the iceberg.
- Stock and flow analysis complement CLDs in the study of policies' transformative potential by helping policy makers understand the system's physical lock-in. Stock and flow analyses shed light on the magnitude of the stocks – one indication of a system's physical lock-in – and the magnitude and speed of change variations in flows may trigger in existing stocks. Stocks and flows are the elements of a system; stocks (e.g. vehicle fleet, public transport infrastructure) change over time due to inflows and outflows and are the "system memory".
- Meadows leverage points framework combines insights from CLDs and stock and flow analysis to identify 12 places to intervene in complex systems, referred to as "leverage points".[36] High-leverage points are places in which a small intervention may lead to large behavioural changes. Low-leverage points are places in which small interventions lead to small changes.

A9: Achieving low national GHG emissions while maintaining healthy life expectancy.

Some countries have been able to achieve high levels of healthy life expectancy at relatively low environmental footprints including GHG emissions. For example, a recent study showed that at levels of average national primary annual energy use between 10 and 75 GJ per person, eight of nine metrics, including life expectancy, infant mortality, happiness, food supply, and access to basic sanitation services, improve steeply and then plateau.[37] Air pollution is the one exception as it plateaus at an energy threshold of 125 GJ $person^{-1}$ across 133 countries. Equitable distribution of current average per capita global energy use of 79 GJ annually could allow the entire world population to achieve 95% or more of maximum performance across all metrics, assuming no other barriers.

Assessment of national data between 1990-2016 also shows that increased environmental footprint and CO_2 emissions appear associated with higher levels of human health and development (measured by healthy life expectancy HALE and human capital HC respectively) up to a certain level of income after which the association is weakened and may reverse.[38] In low- and middle-income countries health outcomes tend to improve with increased resource use, while in high-income countries HALE and HC tended to decline with increasing environmental footprint and CO_2 emissions.

Countries with high health metrics at sustainable EFs and low GHG emissions may offer valuable lessons for progress towards net zero emissions. In 1991 and 2016 only Jamaica (1991) and Sri Lanka (2016) achieved high HALE at sustainable ecological footprint (EF) levels. Of the countries that achieved, or came close to achieving, sustainable EF and high HALE, Albania, Cuba, Ecuador, and Jamaica were highlighted in both years. More work is needed to understand how these countries were able to achieve these outcomes.

These examples suggest that it is possible to achieve good health at low environmental impact, but no major industrialised country has yet shown evidence of rapid declines of GHG emissions in all sectors. Several high- and middle-income countries however get much of their energy from renewables. Transport and AFOLU emissions are likely to be more difficult to reduce without transformative policies and reducing consumption emissions will require demand limitation and circular economy approaches.

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